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RESEARCH MEMORANDUM

A SURVEY AND EVALUATION OF FLUTTER RESEARCH AND ENGINEERING

By NACA Subcommittee on Vibration and Flutter

NACA Headquarters

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A survey and evaluation of flutter research and flutter engineering is presented, with particular emphasis placed on the design of primary fixed surfaces and primary controls. Analyses are made of recent flutter occurrences to delineate past and future problems, and detailed appraisals are given of the status of the various engineering branches involved in the analytical and experimental prediction of flutter.

The report was prepared by a panel of the National Advisory Committee for Aeronautics, Subcommittee on Vibration and Flutter, and has been approved by the entire subcommittee membership. Its purpose is to assay current knowledge in regard to flutter engineering, and to highlight those facets of the subject which will require concentrated research attention if future engineering requirements of the aircraft industry are to be met.

It is pointed out that past design techniques for the prediction and prevention of flutter, while generally successful, have been inadequate in a sufficient number of cases to cause concern. It is anticipated that an increase in both the number and variety of flutter problems will be encountered with future aircraft and missiles. In order to effect successful engineering solutions to these problems, a background of research will be required, and suggestions are advanced in the report for research studies to cope with the anticipated trouble areas.

INTRODUCTION

At the December 1 - 2, 1955, meeting of the NACA Subcommittee on Vibration and Flutter, it was considered desirable to make a survey and evaluation of flutter research and engineering. The underlying reason for this was based on discussions, which summarized, amount to the following statement:

For the design of military and commercial airborne vehicles of the present and the near future (i.e., 5 to 10 years from now), it is mandatory to predict the flutter characteristics to a high degree of accuracy in order to insure safety and satisfy demands for higher performance. Notwithstanding the excellent research on flutter conducted by the NACA and other organizations, and the considerable experience accumulated by the industry over the past years, concern over whether the required design accuracy will be achieved in the design-office is based on a marked increase in the number and type of flutter incidents which have occurred during the last 10 years, and which have resulted in either loss of the vehicle or in severe damage. Corrective action for flutter difficulties has resulted in appreciable expense, in marked delay in getting the vehicle into service operation, and in decreasing performance and increasing maintenance on some airborne vehicles.

For airborne vehicles of the near future, flutter problems are definitely expected to become more severe due to increased speeds, aerodynamic heating, and new configurations. This increase in severity comes at a time when every effort is being bent towards reducing development time and cost.

This survey was prepared by members of the NACA Subcommittee on Vibration and Flutter, and has been approved by the entire subcommittee membership. It is hoped that the report will be of value in an assessment of the current status of flutter engineering, and in arriving at a sound future program of research to fill the gaps in our required engineering knowledge.

Flutter is conventionally defined as a self-excited oscillation resulting from a combination of inertia, elastic, oscillatory aerodynamic, damping and temperature forces. In combination these forces can result in unstable motion (i.e., flutter) which leads to mild or extremely severe structural failures.

This survey is primarily concerned with the flutter problems associated with primary fixed surfaces and primary controls. Many other significant flutter problems are not considered in the scope of this survey, such as those pertaining to heat exchangers for aircraft nuclear power plants, speed brakes, pitot tubes, turbine blades, propellers, helicopter rotor blades, variable leading edges, variable inlet ramps, external masts, refueling drogues, tow targets, armament doors, hydrodynamic planing surfaces, parasite aircraft, and panel flutter.

As a basis for the further discussion, it is of interest to examine the speed-altitude-temperature regimes that are of concern at the present and in the near future. Figure 1 presents a Mach number-altitude plot of these regimes which are divided into the following very approximate catagories:

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Regime I - Transonic speed airborne vehicles. Subsonic incompressible flow, subsonic compressible flow, and transonic flow are prevalent. Temperature effects are negligible.

Regime II - Low supersonic speed airborne vehicles. Flows of Regime I and in addition supersonic flow are prevalent. Temperature effects are either negligible or of minor importance.

Regime III - High supersonic speed airborne vehicles. Flows of Regimes I and II are prevalent. Temperature effects are of considerable concern.

Regime IV - Hypersonic speed airborne vehicles. Flows of Regimes I and II and, in addition, hypersonic flow are prevalent. Temperature effects are of major concern.

Naturally, the regimes shown in figure 1 do not apply exactly for a particular airborne vehicle - rather they are order of magnitude envelopes wherein certain types of oscillatory aerodynamic and temperature phenomena are prevalent which are of interest from the flutter viewpoint. The explanatory notes in figure 1 also indicate the maximum temperature which would be encountered in each regime. Of prime significance is the fact that industry is (or will be in the very near future) building airborne vehicles to operate in all of the regimes shown in figure 1; flutter engineering is unfortunately considerably behind this development pace, as will be seen later in the report.

The following section of the report contains a historical survey and analysis of actual flutter incidents which have been experienced with military aircraft during the period from 1947 to the present. This provides background for the subsequent sections, which deal with the design-office and research state-of-the-art of flutter prediction engineering, both from the theoretical and experimental standpoints. An overall summarization concludes the report. Throughout the discussion, an attempt is made to clarify the areas which require research if future engineering requirements are to be met.

SURVEY OF RECENT FLUTTER OCCURRENCES

Table I presents a summary of flutter incidents which have occurred on U.S.A.F. and Navy aircraft in the period between 1947 to the first part of 1956. The incidents are broken down under each year. The U.S.A.F. incidents include both airplanes and missiles; the Navy incidents are for airplanes only. No civilian or commercial aircraft were considered in compiling the table.

Thirteen flutter incidents occurred during 1947 to 1951. Of these, approximately 10 were of the control-surface, spring-tab, and trim-tab variety whose characteristics were quickly understood and for which remedies were readily available on the basis of state-of-the-art know-how (irreversibility and revised mass balance). This of course does not imply that accurate flutter aerodynamic derivatives were available to give theoretical prediction results of high accuracy, such as are required for adequate design safety.

Except for one case of tip-tank flutter, which was a special flutter investigation, no cases of bending-torsion flutter occurred, since the strength required for structural purposes was sufficient to result in adequate flutter margins of safety. In this 1947 to 1952 era, the average bending-torsion flutter margin of safety was probably of the order of 30 percent or higher.

Two items deserve special attention. These are the tip tank and the stabilizer torsion-mass unbalanced elevator flutter cases. These incidents in retrospect could conceivably be interpreted as the first experimental evidence of serious flutter problems to come, and the greater actual importance of flutter in controlling the design of aircraft.

The next era considered is the period from 1952 to early 1956. Of 41 incidents, 13 are cases of trim-tab, spring-tab, and control-surface flutter (partially balanced and mass unbalanced control surfaces included). Most of the trim-tab flutter cases occurred because of loss of the actuating system stiffness, which should be preventable by adequate design. The nine cases of spring-tab and control-surface flutter are approximately equal to the number which occurred in the 1947 to 1951 era. Thus, this problem area is still not under control, and more accurate and dependable theoretical procedures, experimental data, and design criteria are needed, especially in view of a proposed trend towards mass unbalanced control surfaces and higher speed aircraft having smaller thickness ratios.

Additional examination of the latter time period reveals that six cases of external store flutter (including pylon suspended engines) have occurred, compared to one in the previous time period. The extreme importance of the external store problem from a flutter viewpoint is clearly evident.

The transonic speed regime has caused the occurrence of control-surface and tab buzz, and combined control-surface flutter buzz. Twenty-one cases are tabulated for the 1952 to 1956 period. The only known cures or preventive means are hydraulic dampers, the North American splitter configuration, or very high stiffnesses in the actuating system. Since these buzz cases total more than half of the flutter incidents in the latter time period, it is obvious that additional information leading to a basic understanding of the phenomenon and its avoidance by efficient means is mandatory.

The all-movable control surface was early suspected as a possible source of flutter difficulties. This early suspicion is substantiated by the four cases which occurred in 1953 and 1955. It is expected that the all-movable surface will continue to be a very serious, first-magnitude flutter problem area for years to come. Much information is considered necessary and essential to indicate design criteria and to insure its prevention at an early design stage.

One known case of T-tail flutter occurred in 1952. This type of configuration may be considered somewhat similar to the external store problem in that frequencies are relatively low and critical frequency ratios are possible. Like the external store problem, the T-tail, therefore, is expected to be a serious flutter problem and its service occurrence on aircraft may definitely increase.

It is estimated that current flutter velocity margins are in many cases of the order of 15 percent, the minimum acceptable. The flutter cases described indicate that design difficulties may be encountered in obtaining the desired safety margins for T-tails, all-movable stabilizers, and external stores.

It is difficult to review the various flutter cases fairly and objectively and decide which could, or should have been predicted on the basis of the state of the art. However, in most cases it should be realized that flutter studies of reasonable extent were made before the airplane flew. Thus, state-of-the-art design criteria and theoretical calculations, regardless of the precise reasons, may be deemed inadequate.

Nine flutter cases can be attributed to malfunctions. For about six cases the theory is definitely inadequate to permit proper engineering treatment. No reliable theory or basic understanding was available to make realistic guesses for the 21 cases involving buzz. In 21 cases the possibility of the incidents could have been predicted if accurate flutter derivatives were available, and if the flutter engineers had the foresight to investigate the pertinent modes despite the lack of occurrence of the particular type of flutter up to that time. In evaluating the above statements, the old story of better hindsight must be considered. However, it is foresight for which flutter engineers are paid.

Concerning the future, some new design configurations which may present additional flutter problems are:

1. Floating fuel tanks

2. Tip controls

3. Rotatable or extendable control surfaces

In addition, there exists the definite possibility that future flutter cases may not involve the simpler fundamental modes of vibration which seem to define most of the cases in the present survey. Higher-order modes (possibly resulting from the effect of temperature on aeroelastic characteristics) may occur in the high Mach number and high dynamic pressure regimes, even though adequate safety for fundamental modes has been provided. This contention is borne out in part by results of NACA rocket flutter tests of delta wings and chordwise flutter model tests. The possibility of flutter in higher modes obviously will make the task of the flutter engineer much more difficult and will significantly increase the area for which accurate knowledge is necessary.

FLUTTER DYNAMICS

In order to cope adequately with flutter design problems, it is obviously necessary that the engineer have an understanding of the physical mechanisms underlying flutter phenomena. The complexity of flutter engineering arises from the fact that at least three of the classical fields of mechanics must be simultaneously kept in mind when dealing with any flutter circumstance - structures, dynamics, and aerodynamics are inseparably intertwined.

In the development of flutter as a rational branch of aeronautical engineering, it was only natural that classical vibration theory be used as the starting point. In all essential respects, a complete understanding had been reached regarding the vibrational behavior of undamped elastic systems, executing small vibrations, and acted upon by externally applied forces of known magnitudes. This body of knowledge extended to both continuous systems (such as an aircraft structure), and to systems composed of interconnected springs and discrete masses. The Lagrangian approach and the work of Rayleigh-Ritz also provided the important clue as to how a continuous system could be replaced by its simpler equivalent of connected springs and discrete masses, that is, by a finite number of natural modes with suitable elastic and inertial coupling.

Finally, classical theory had extended all of the knowledge regarding undamped systems to cover the case of vibrating structures containing a small amount of internal viscous damping.

It was soon found, however, that an understanding of flutter mechanisms required a considerable extension of these important classical concepts. To begin with, the external (aerodynamic) forces acting on a flutter configuration are not known in advance; rather, they are a result of the vibrations themselves. It is for this reason that flutter oscillations are of the "spontaneous" variety; a small disturbance of the system under steady conditions causes air forces to act which perpetuate the disturbed motion. A new branch of dynamic theory, taking into account the particular character of flutter air forces, thus had to be developed.

In addition, it became clear that the classical concept of internal, viscous damping was not suitable for describing practical aircraft structures. Rather, a new kind of damping - so-called "structural" damping - had to be devised in order to bring theory and observation into approximate agreement. Of purely empirical character, the structural damping concept essentially entails internal damping which is amplitude-sensitive, but frequency-insensitive. Once again, new theoretical developments were required to permit an understanding of the system behavior with this new type of internal energy dissipation. It is also safe to say that a more rational description of the nature of structural damping is a requirement for future research.

While progress along these new lines of study has been continuous, it is generally correct to say that the rate of progress has been slow, particularly when compared with the steady increase in the complexity of practical aircraft configurations. Generalities regarding flutter behavior are notable only for their absence, and even the experienced flutter practitioner will admit to frustration in attempting to understand many practical phenomena on physical grounds. Even greater difficulties arise when attempting to synthesize an optimum, flutter-free structure, as compared with the simpler problem of analyzing the flutter mechanisms inherent in a configuration fixed in advance.

Much further research is therefore needed along the lines of understanding the fundamental physical character of the flutter problem. Certain flutter cases are of the so-called "violent" variety, that is, small speed increases cause a well-damped system to engage suddenly in violent vibrations of catastrophic amplitude. Other flutter cases are "mild" - even at the critical flutter speed, the oscillations are nonviolent and appear to be of self-limiting amplitude. Our knowledge of the reasons underlying these two types of behavior is as yet incomplete, despite the great practical importance of being able to avoid "violent" flutter designs.

Nonlinearity effects in flutter are known to affect significantly the system performance around the critical speed, yet here again only a start has been made toward achieving a real understanding of the pertinent mechanisms. A similar remark holds true regarding the effects of high temperature on flutter behavior.

It is clear that immediate need exists for the formulation of flutter principles which permit the designer to understand the engineering nature of flutter, and which provide basic design principles for flutter avoidance in modern, complicated configurations. These goals will be reached only through additional research on the broad subject of flutter dynamics, much as was accomplished earlier by classical vibration theory for simpler types of vibrating systems.

ANALYTICAL PREDICTION OF FLUTTER

For the design-office prediction of airplane flutter, a knowledge is required of the mass, stiffness, oscillatory aerodynamic, damping, and thermal characteristics of the airframe. In view of the fact that flutter analysis entails so comprehensive a coverage of engineering information, interrelating a number of the classical engineering branches, it is hardly surprising that considerable difficulties are encountered in arriving at accurate engineering results for complicated systems.

While a variety of techniques are used by flutter groups within the industry, the conventional procedure for the flutter analysis of a new airplane can be divided into the following main tasks:

Calculation of the natural frequencies and natural vibration mode shapes which are pertinent to the anticipated flutter motions of the airplane.- In order to calculate these modes accurately, the mass, stiffness, and damping and the transient and steady temperature effects on these parameters must be understood.

Calculation of the oscillatory aerodynamic forces.- This step entails the computation of the air forces which are active during the flutter motions and represents essentially a problem in unsteady aerodynamics.

Calculation of the flutter velocities for various flight conditions.- With the mechanical and aerodynamic performance of the structure understood, the flutter equations of motion can now be formulated and solved for the critical velocities.

Calculation of the aircraft response to a forced vibration, should such information be desired for purposes of flutter flight testing or to provide more extensive analysis of ground vibration data.

The following remarks are in order regarding each of these steps in rational flutter analysis.

Calculation of Natural Frequencies and Natural Vibration Mode Shapes

The first step which the flutter analyst usually takes in a theoretical flutter computation is to calculate those natural frequencies and corresponding vibration mode shapes for the structure (in still air) which will probably appear in the flutter motion. This preliminary calculation makes use of basic information on the mechanical characteristics of the structure - data pertaining to its elastic characteristics, to the distribution of masses supported by the structure, and the mass of the structure itself.

The calculation of these modes is an essential preliminary to the actual flutter velocity computation when a Rayleigh type flutter analysis is employed. In the Rayleigh type analysis, the flutter motion of the airframe is represented by a combination of motions of certain natural modes, chosen at the discretion of the analyst.

It should be noted that techniques of flutter analysis other than the Rayleigh type are now becoming somewhat more popular, thus not requiring that natural modes be employed as degrees of freedom in the flutter calculation. A significant practical importance nonetheless attaches itself to natural mode studies. Specifically, through the medium of the ground vibration test of the prototype aircraft, it is possible to compare the calculated mode frequencies and shapes with those observed during the vibration test. This affords an important and direct check of the degree to which the mechanical properties of the structure have been adequately accounted for in the theoretical calculations. Regardless of the extent to which natural modes are used directly in the determination of critical flight velocities, therefore, it is expected that natural mode calculations and ground vibration tests will continue to be a standard tool of the flutter engineering group.

For more or less conventional aircraft of low and medium performance ranges, with moderate to high-aspect-ratio wings and without the complication of large, sprung masses attached to the structure, reasonable success can be achieved in calculating the lower modes of the system. Thus, for example, based only on mass-distribution estimates and stiffness calculations made on the basis of engineering drawings of the structure, the fundamental and next highest bending and torsion modes for primary surfaces can usually be predicted with good accuracy, although it is common experience that the mode shape accuracy will not be as acceptable as the natural frequency calculations. This reasonably acceptable state of the art holds even where fuselage flexibility is of importance, and where rigid body motions are coupled with elastic motions.

With the current trend toward unconventional aircraft, the state-of-the-art in regard to natural mode calculations has unfortunately deteriorated substantially. In the case of smaller, high-speed aircraft, the use of wings of very low aspect ratio and of complex internal structure has greatly reduced the design-office effectiveness of natural mode calculations. In the case of large, high-performance aircraft, which are relatively flexible and generally characterized by a variety of external stores and elastically suspended masses, the needs of the flutter analyst have extended beyond the lower modes and into the higher vibrational modes. Here also, the calculation techniques have not maintained the required high order of engineering accuracy.

It should also be mentioned that to date there are no theoretical methods available for estimations of the structural dampings associated with the various vibration modes; these are generally obtained experimentally during the ground vibration test.

The reasons for the increasing difficulties associated with natural mode calculations are not difficult to ascertain. The current methods of structural analysis, specifically in regard to stiffness estimations, are inadequate when a complicated structure must be dealt with. Stated differently, current techniques require an idealization of the structure into principal structural components, a procedure which is not entirely consistent with the actual behavior of the system. Typical sources of difficulty are in the consideration of shear deformation in estimating bending stiffness, in the neglect of differential bending of structural elements in establishing torsional stiffness, and in the inadequate consideration of reductions in bending stiffness due to skin buckling. The appearance of the thermal problem, with the strong effect of transient temperatures on structural stiffness, is substantially magnifying the difficulty of the flutter analyst. The problems of external stores and sprung masses are also becoming more severe; such questions as the determination of the effective masses of liquid fuel, heavy retractable components, etc., cannot be adequately handled at present.

It is clear, then, that considerable effort is warranted in research to improve current methods for calculating natural frequencies and natural vibration mode shapes. Valuable information could be obtained from a systematic study of a group of aircraft representative of the fighter and heavy bomber categories. Calculations of the mode shapes by the best available methods, compared with accurate ground vibration observations of the prototype aircraft, would probably disclose suitable avenues for refinement of the analytical design techniques. It must be appreciated, however, that such studies are both expensive and time consuming; certainly nothing of this order of magnitude is presently incorporated in research in this country. While each company attempts to profit from its design experiences with each new aircraft model, the urgency of engineering design schedules precludes a systematic study of the type visualized here.

The problems inherent in natural mode calculations for complex aircraft have led to the suggestion of alternative approaches to obtain the required design information. Thus, dynamically scaled models have been suggested for use in the determination of vibration modes during the design phase when the prototype is not available. Since the construction of a dynamically scaled model of practical simplicity entails a thorough understanding of the structural problems of the prototype, it can be seen that substantial advantage is not gained by going in this direction.

To refine knowledge of the stiffness characteristics of the airframe, it has also been proposed that measurements be made on the full-scale prototype. This has the obvious disadvantage of having to await the availability of the prototype aircraft, and further poses significant technical complications. In order to obtain stiffness measurements of the necessary accuracy for certain important portions of the structure, such as the root regions of wing surfaces, it is found that loads must be applied which exceed the design limit loads.

In summary, therefore, it can be said that the present stage of the art is not entirely satisfactory in regard to natural mode calculations for present and future aircraft. The importance of such information for the flutter engineer is sufficient to cause considerable concern, and an aggressive and expanded research effort in this area seems warranted.

Calculation of Oscillatory Air Forces

The proper determination of oscillatory aerodynamic forces in flutter analysis is vital, as without these forces we are dealing with conservative or structurally damped mechanical systems. Examination of the mathematical equilibrium condition which defines flutter, or of the function giving the aerodynamic work per cycle of oscillation, shows that, at flutter, the structural dynamics and aerodynamics are intertwined so that accuracy is generally needed in both of these parts if accuracy is to be achieved in the end result. Moreover, the type of aerodynamic information required depends on the choices made for the structural basis of analysis. Usually this basis is a Rayleigh, modal-type analysis, though sometimes it is an influence function type of analysis which avoids the modal approach.

Many technical papers and monographs, and a few excellent books are now available which consolidate the present theoretical position. In brief, this position is: Two-dimensional potential flow methods used in strip analysis or Rayleigh type analyses are well developed. Three-dimensional flow methods are in a continuing state of flux and are currently being defined and evaluated.

Status of two-dimensional linearized subsonic- and supersonic-flow theory: The aerodynamic edifice of the two-dimensional linearized oscillatory flow theory is now essentially completed. Adequate tables may be said to exist for most routine purposes for the complete Mach number range, though special mode patterns, such as modes of camber deformations, or some control-surface problems, may still require considerable labor. Table II is a list of available numerical tables and the ranges of parameters of interest (such as reduced frequency, Mach number, and aileron parameters) covered by them.

Strip-analysis methods: The relatively easy availability of two-dimensional numerical results and the extreme difficulty of treating, even by linearized methods, the air forces and moments on wings vibrating in an elastic mode, have led to the adoption of two-dimensional methods in strip analysis. In this process each vibrating strip is handled as though part of an infinite wing having the same normal velocity distribution as that existing at the vibrating strip, and all strip effects are integrated spanwise in accordance with the chosen mode of vibration to yield the proper generalized forces. For sweptback and tapered wings care must be exercised to allow for the effect of average effective yaw of the infinite wing representing the local strip.

It has turned out that this strip-analysis process has yielded rather unexpectedly good results for wings of high aspect ratios, as determined by experiments with simple wing models. It has also helped to serve as a means for presenting experimental information in a coherent fashion for wings of low aspect ratio. In this manner, experimental correction factors for criteria or trend studies can be formulated without actually proceeding to rigorous three-dimensional flow theories. For example, the two-dimensional theory has served usefully in various trend studies that have been carried out with physical or mathematical-type electrical analogs. It is recognized, however, that lower-aspect-ratio wings for high-speed flight require a three-dimensional treatment structurally and aerodynamically if accuracy is to be attained, or if assessment of simpler methods is to be evaluated properly. Thus, the available theory employing strip-analysis methods is limited in its scope.

Three-dimensional flow methods: The treatment of an oscillating wing in an elastic wing mode by three-dimensional flow methods is, in general, not in a satisfactory state. The methods that have been used may be loosely termed lifting-line, multiple-lifting line, and lifting-surface methods. It cannot be maintained that any one of these methods has been proved to result consistently in useful practical developments suitable for routine applications. The lifting-surface methods have recently been used to compare air loading distributions and flutter results obtained in illustrative examples for comparison with those obtained using two-dimensional flow methods. These comparisons have shown that the surface methods ought to be pursued in the direction of systematization for routine applications, and that these will require large-scale computing machinery methods.

The lifting-line methods that have been developed in the past 20 years number a score or more. Many of these have been patterned to yield the Prandtl lifting-line result for the limiting case of steady flow. This is believed to have been an unfortunate simplification. The earliest of these methods is that of Cicala; subsequent well-known methods are those of Küssner, as applied by Küssner and Dingel, and of Reissner, as applied by Reissner and Stevens. It happens that the various methods are essentially equivalent, and that those of Küssner and Reissner are actually identical in their application. Shortcomings of the line methods appear to be their inadequate treatment of the tip and, as the aerodynamic center of pressure and its spanwise variation are important flutter parameters, their inability to define the moment characteristics any more reliably than the two-dimensional treatment. The moment coefficient appears to be a more sensitive indicator of the refinement of an aerodynamic theory than the lift coefficient. Another drawback in practice concerns the question of conservatism or nonconservatism of the flutter results, as it often has happened that the three-dimensional line methods have been unconservative, that is, they have erred on the unsafe side.

It appears necessary to go to multiple-line methods or to surface methods to obtain any substantial improvements, or to be in a position to judge the degree or range of applicability of the line methods. One approach which has been indicated but not developed numerically is the extension of the line methods to two lines, resulting in two relations to account for spanwise variations of both the lift and the moment. This approach has been used in steady low-speed flow on small-aspect-ratio swept and delta wings and has led to rather good results.

Lifting-surface methods for oscillating finite wings: A kernel function method has recently been employed for three-dimensional flow which is a direct extension of the method originally used to obtain results for two-dimensional compressible flow. Results obtained to date indicate that the procedures lead to reasonable and accurate results as far as can be judged. The methods appear to be the most promising for achieving accuracy in the theoretical results of any of those on the horizon. The procedures can be applied separately to subsonic, sonic, and supersonic speed regimes. For the latter regime, it is too early to state that the advantages will exceed those of other available three-dimensional methods.

Methods for supersonic speeds: A number of mathematical methods exist for a few plan forms undergoing rigid body-type motions. However, the need is for methods readily applicable to elastic modes. Analytical methods that have shown some promise involve expansions of the air forces in a parameter such as the reduced frequency, the expansions being applied for mathematically defined modes of deformation of the vibrating wing, as terms of a power series in spanwise and chordwise coordinates, for example.

A recent numerical development for supersonic speeds for the wing surface problem has been termed a "box" method. This procedure involves separation of the plan form into convenient box-shaped areas, and is essentially an aerodynamic influence coefficient method which lends itself to routine systematization, particularly for the case of all edges supersonic. Several variations of the box method, in the choice of boxes, and in extensions to plan forms with subsonic leading edges, are in the process of development.

High supersonic speeds - effects of thickness: A useful procedure for taking account of thickness and camber effects for high supersonic speeds is based on the following concepts: (a) independence of top and bottom surfaces, (b) the use of piston theory, and (c) the use of a more accurate pressure-velocity relation than the linear one. The method may be readily routinized and should provide insight into aerodynamic effects of thickness, and assist in connection with analysis of flutter effects associated with aerodynamic heating for high supersonic speeds.

Status of some experimental checks on flutter calculations: A brief and incomplete listing of experimental checks is given in table III. For high-aspect-ratio wings, this agreement is good to excellent, perhaps within 10 percent. For low-aspect-ratio wings and for control surfaces results are much less satisfactory. However, for elastic wing modes and low-aspect-ratio wings, experimental results are insufficient in general to provide proper evaluation of the theory. Additional remarks on experimental checks will be found in the later section of the report titled "Experimental Flutter Prediction Techniques."

Concluding remarks: There is a great need for development of supplementary or modified theories to account for nonpotential flow effects. Control surfaces of all types, high angle-of-attack components, components having separated flows or operating within separated flows, wing-body combinations, are far from understood in the unsteady aerodynamic regime. The effort along theoretical lines should proceed, not only in making available and usable the existing formal results, but also in advancing the art towards including real (nonpotential) flow effects.

Calculation of Critical Flight Velocities and Flutter Frequencies

Once the mechanical and aerodynamic characteristics of the flutter system are understood and can be represented mathematically, the equations of motion for the system can be formulated and solved for the critical flight conditions. Principal interest is attached to the estimation of the flutter speeds for various flight configurations, the flutter frequency also being of engineering significance. In modal-type analyses, the flutter frequencies are of interest in permitting the designer to make certain that all natural modes surrounding the flutter frequency have been accounted for; in addition, it will be pointed out later that a knowledge of the flutter frequency is of considerable importance when planning flight flutter tests.

It has already been mentioned that several possible approaches can be used in formulating the equations of motion. The most conventional type of analysis is based on the Rayleigh modal approach, wherein the flutter motion of the system is represented in terms of contributions from pertinent natural modes. A second type of analysis, which is becoming more popular because of its adaptability to the treatment of low-aspect-ratio wings and complex structures, avoids the modal approach and employs an influence-coefficient type of dynamic analysis. For calculations by influence-coefficient techniques, the motions of segments of the airframe are treated as degrees of freedom, and the equations of motion for the various segments are formulated. This differs from the modal approach in that each natural mode used as a degree of freedom in a modal analysis presumes a continuous deflection and motion pattern for the entire airframe.

It appears that the influence-coefficient type of formulation of the equations of motion will become more popular in the future, since this has some calculational advantages when employing large, automatic digital computers for the numerical studies. Further impetus for this type of analysis will result when suitable methods are devised to measure directly structural influence coefficients during static test of the prototype airframe. It should be noted that the problem of calculating the natural modes for the airframe is not necessarily penalized when an influence-coefficient type of analysis is formulated; by simply deleting the terms in the equation which represent the aerodynamic forces, computation will yield the mode shapes and frequencies required to check ground vibration tests.

As yet, the relative advantages of the modal versus influence-coefficient analyses are not entirely clear, and further research will be required to disclose the particular merits of each. From the theoretical dynamics point of view, it is probable that both are equally effective, that is, with a given engineering understanding of the problem, each will yield results of about the same accuracy. However, the relative amount of computational effort may be less in one case than the other, partly because a simpler and more direct coding procedure can be used for the automatic computer.

Regardless of the type of analysis employed, the final step in a flutter evaluation is the calculation of the roots (eigen values) and, in some cases, modes (eigen vectors) of the dynamic matrix, the order of the matrix being the same as the number of degrees of freedom treated in the analysis. Since computational complexity increases markedly with the order of the matrix, it is clear that a minimum number of degrees of freedom, consistent with the desired engineering accuracy, should be used. For complex aircraft, general conclusions are not yet available regarding a suitable choice of numbers of degrees of freedom. The discretion of the analyst is still the deciding factor in such choices, which is perhaps an inevitable accompaniment of advanced engineering design studies.

The numerical techniques currently employed for solving the equations of motion are generally adequate for the problem at hand. The availability of large-scale computers in the aircraft companies will undoubtedly permit an increase in the size of the flutter calculations, enabling more degrees of freedom to be taken into account without substantial increases in engineering labor and time, and it appears that sufficient attention is being given to the associated computing problems by numerical analysts to cope successfully with the added computational complexities.

The accuracy of solutions for critical flutter velocities are, of course, directly dependent on the precision with which the mechanical and aerodynamic counterparts of the problem are included in the equations of motion. It has already been pointed out that, in many instances, the required design accuracies cannot be achieved because of gaps in our knowledge of these elements of the problem.

It is worth mentioning once again that for many systems the structural damping plays a powerful role in determining the critical flight velocities. At the present time, only past experience and the ground vibration test afford estimates of the magnitude of this parameter. The structural damping coefficient varies from one natural mode to the next, a consequence of the empirical nature of the structural damping concept, and the variation of this parameter with aircraft life and operating conditions is not thoroughly appreciated. Our knowledge in this area is thus seen to be definitely inadequate.

It is probable that further research effort should be directed toward overall appraisals of the accuracies of flutter analyses. This is perhaps best done through the medium of comparing calculated results with those obtained from systematic wind-tunnel and flight flutter tests (see later discussion). However, while the principal objective of a flutter analysis is the calculation of flutter speeds, a more thorough understanding of the accuracies required in the mechanical and aerodynamic contributions in order to achieve suitable precision in the flutter-speed estimations is both a worthwhile and necessary research objective.

Forced Response Computations

From the theoretical point of view, if the natural modes of vibration in still air and the flutter modes of the aircraft system can be calculated accurately, then it should be possible to trace the behavior of the system when it is forced to oscillate at any combination of flight velocity and oscillation frequency. Conversely, if correct calculations can be made describing the system behavior when excited by external forces at various frequencies in the flutter range, and when the aircraft is in flight at velocities moderately below the flutter velocity, then flutter predictions of high accuracy will follow automatically.

For purposes of prototype flight testing to determine flutter margins, it is obvious that flight at the flutter speed is impractical; however, the aircraft can be excited by external forces into vibration at speeds below the critical velocity and over a range of frequencies covering the flutter range, and the flight observations can be compared with calculations covering the same test circumstances. If the two are in agreement, considerable confidence can be attached to the theoretical flutter velocity predictions. It is thus seen that considerable interest is attached to forced response studies in flutter engineering.

Forced response studies, that is, studies of the response of the aircraft to externally applied oscillatory loads, is not only of interest in connection with flight-flutter programs, but also provides the engineer with an estimate of whether the flutter mode will be a "mild" or "violent" one. Under forced vibration conditions, the approach to a violent flutter mode will show a rapid decrease in the system stability, starting just below the actual flutter speed. A mild flutter mode is generally characterized by a gradual loss in system stability which is observable well below the critical flight condition. While it has not yet been absolutely demonstrated that these characteristics serve to define the difference between mild and catastrophic flutter, it is not unreasonable to presume that this is the case.

For a variety of reasons, therefore, increasing attention is being given by industry and research agencies to forced response studies. In the case of ground vibration testing, the forced response measurements define the system damping, and comparisons of measurements and calculations over a frequency range give added confidence to the fact that the mechanical properties of the airframe are properly represented in the calculational scheme.

In general, it may be said that very little experience indeed is currently available in regard to forced response techniques, particularly in the flight region. With the increasing importance of this facet of flutter engineering, it can also be concluded that our research effort is sadly lacking in this area.

Comparisons between calculated and observed forced response characteristics of aircraft in flight pose, at present, very substantial research problems, both in regard to the technical aspects of such studies and the associated costs. However, it would be most valuable if such studies were undertaken systematically for a group of representative aircraft. This research background will then permit the gradual integration of this important technique into industrial practice. It might be mentioned that certain of the aircraft companies are already using flight response studies as engineering tools, and are doing so without the benefit of an adequate background of research knowledge and experience. This is a dangerous, although perhaps expedient, course of action; it cannot be justified on the grounds of safety, save where a high degree of certainty exists that the anticipated flutter will be of the mild variety. Some evaluation of the degree of risk involved in forced response tests in flight may be obtained from wind-tunnel testing of scaled elastic models, preferably with forced excitation.

EXPERIMENTAL FLUTTER PREDICTION TECHNIQUES

The subject of experimental flutter prediction techniques is discussed under the following headings:

(1) Natural frequencies, natural vibration mode shapes, and forced responses

(2) Measurements to determine stiffness

(3) Oscillatory aerodynamic forces

(4) Flutter models

(5) Flight flutter testing

Natural Frequencies, Natural Mode Shapes, and Forced Responses

The role of the ground vibration test in flutter engineering has already been reviewed earlier in the report. However, it may be helpful once again to summarize the pertinent arguments.

It has already been pointed out that the first step in a theoretical flutter computation is usually the calculation of a few of the natural frequencies and corresponding vibration mode shapes of the structure in still air. This preliminary calculation makes use of the basic engineering information on the mechanical characteristics of the structure, that is, the data relating to the stiffness and inertial characteristics of the airframe. If a Rayleigh type analysis is to be used for the actual flutter computation, these natural modes will later be employed as degrees of freedom.

The important point to be emphasized here is that in a modal type of approach to the dynamic analysis of the airframe, the mechanical properties of the structure can be represented wholly in terms of the mass distribution, the natural frequencies of the airplane at rest, the natural vibration mode shapes, and the structural damping. Except for the mass distribution, these properties are all subject to verification in a properly conducted ground vibration test. (Structural damping can be determined by measuring the rate at which vibration dies out when exciting forces are removed.)

When scaled flutter models are employed it is customary to conduct vibration tests in still air on both model and airplane. Direct comparison of natural frequencies and mode shapes then provides a relatively rapid check with regard to mass and stiffness distributions of the overall similarity between model and airplane. When flutter analysis is performed on an analog computer of the passive network type, the procedure for using ground vibration test results to evaluate the accuracy of the electrical simulation is essentially the same in principle as the method used to check the scaled flutter model.

In brief, the ground vibration test is, for the flutter analyst, a major source (and often the only source) of basic experimental data pertaining to the mass and stiffness distributions (apart from aerodynamic characteristics) of the airplane. The results of this test are intended to provide him with an overall evaluation of airframe parameters that he has employed in his flutter predictions. If the check is unsatisfactory, measured ground modes and frequencies may be used directly in a final flutter analysis. The importance of this check to the flutter engineer is comparable to that of the static proof test for the stress man.

Basic concepts: The plan of a typical airplane ground vibration test is generally formulated in terms of concepts which are derived from vibration theory - the theory of small amplitude vibration of elastic structures with small damping. In fact much useful vibration theory is concerned with ideal systems having no damping whatsoever. Mathematical analysis indicates that such idealized frictionless systems should exhibit characteristic natural frequencies of vibration, and that with each characteristic frequency there is associated a definite vibration form or mode of vibration (commonly called a normal mode). When an undamped structure is set into vibration in one of its normal modes and left to itself, theory indicates that the vibration will continue indefinitely at the natural frequency without change in shape and without loss of amplitude. When one or more sinusoidal forces of equal frequency are applied to suitable points of the structure, it responds by vibrating at the same frequency. If the exciting frequency is made to coincide with one of the natural frequencies of the structure, the amplitude of vibration becomes exceptionally large (theoretically infinite if the structure is undamped). This phenomenon is called resonance. Furthermore, if the resonant frequency is reasonably well separated from other neighboring natural frequencies, the form of the forced vibration will be practically the same as the normal mode of free vibration corresponding to the resonant frequency.

Experience with practical metal airplane structures indicates that the damping due to internal friction is sufficiently small to justify the assumption that natural frequencies and mode shapes are unaffected by it. Hence, it is reasonable to expect that mode shapes and natural frequencies determined from ground resonance tests should agree with results of computation neglecting damping, and with data from resonance tests on scaled models - if both the computations and model design were based on correct elastic properties and mass distribution data.

Testing methods: Since mode shapes and natural frequencies are influenced by the manner in which the airplane is supported, the design of a suitable support system for ground testing is of some importance. In many cases it is considered desirable to employ a soft suspension, so that free body modes are obtained to a close approximation; this can be accomplished with relative ease if the airplane is small. However, such a condition is exceedingly difficult to obtain for a very large airplane, since the support must provide great strength to support the weight of the airplane, a high degree of flexibility, very low friction, and sufficient stability to safeguard the airplane. Fortunately, it is possible to accomplish most of the necessary objectives with the airplane on stiff supports. Therefore we may regard the development of a flexible support system for very large airplanes as a desirable objective, but it need not be given the highest priority.

Perhaps the most important requirements for a satisfactory support system are:

(a) The support reactions must be statically determinate. (Otherwise the support system may impose undesirable or unknown restraints on the airplane structure.)

(b) The supporting structure must either be very rigid or its elastic deflection rates must be accurately known. If the primary purpose of the vibration test is to check the flutter model, then it will be sufficient to test the model under comparable conditions. On the other hand, if free body modes are wanted, they may be obtained by a supplementary analysis using the measured modes together with rigid body displacements as degrees of freedom.

Sinusoidal forces are generally provided for ground vibration testing of airplanes by means of electromagnetic exciters driven by electronic power supplies and control equipment. Commercial pickups, amplifiers, and recording oscillographs are usually employed for measurement and recording of data. Miniaturized equipment of the same general type is employed for model testing. Extensive reading of records and manual analysis of data are required.

Evaluation of current performance: Current procedures are reasonably satisfactory for ground resonance testing when only low order modes are required and the pertinent natural frequencies are well separated. Even in these cases it is highly advantageous to employ several exciters, with separate controls and equipment for rapid visual phase comparison between pickup outputs, to assist the operator in obtaining the pure normal mode at each resonant frequency.

In general, it can be said that a very serious inadequacy exists whenever it becomes necessary to deal with complex modes of an airplane having natural frequencies close together. This situation is apt to occur on any airplane if a large number of modes of the entire structure are required, due to interaction between components (it can occur, e.g., if uncoupled frequencies of wing and empennage should happen to coincide). The problem is particularly troublesome and practically inevitable on large, flexible aircraft carrying external stores and/or flexibly mounted wing engines. One way in which the difficulty manifests itself is through an inability to get the various masses of the system moving in phase with each other at resonance. Since the relative phases of motion of different parts of the structure exhibit erratic variations, it is clear that the shape of the response cannot be regarded as a normal mode. This is further confirmed when the exciting forces are removed. Each of the modes which is present in the steady forced vibration then decays at its own natural frequency; since these natural frequencies are slightly different, beats appear. Under these circumstances it is impossible to determine how much of the discrepancy between forced response and calculated mode shape should be attributed to inadequate test technique and how much to errors in vibration analysis.

The work of Lewis and Wrisley[1] is a very important contribution to the development of a satisfactory system for airplane ground vibration testing. The basic principle of this method is that the structure should be regarded as a collection of lumped masses, and an exciter should act near the centroid of each mass in the direction of vibratory motion. All exciting forces are in phase or in phase opposition to each other (relative phase angles restricted to 0° and 180°); force amplitudes are independently adjustable. The recommended test procedure for obtaining a pure mode is to adjust each force in proportion to the product of mass and displacement. If the frequency is tuned to resonance and adjacent natural

[1]Lewis, R. C., and Wrisley, D. L.: A System for the Excitation of Pure Natural Modes of Complex Structures. Jour. Aero. Sci. vol. 17, no. 11, Nov. 1950.

frequencies are not too near the exciting frequency, then the process will converge to yield the desired normal mode. When convergence has been achieved, the distribution of exciting forces is proportional to the vibratory inertia loading in the desired mode; because of the orthogonality relations between modes, none of the unwanted modes are excited. This procedure has been used very successfully on simple lumped mass systems with varying amounts of damping added to the system. The resulting measured modes exhibit the expected characteristics of pure normal modes (uniformity of phase throughout the structure, absence of beats in decaying oscillation when exciting forces are removed); also they are in close agreement with theoretical computed modes of the system.

The system of Lewis and Wrisley has also been used a few times for demonstration purposes on small airplanes. However, in spite of its attractive features, this approach has never been applied systematically for testing large aircraft where mode interference is a serious problem. The reason for this is that a very large investment in equipment would be required, because of the number of exciters and associated control elements needed to match a lumped mass idealization of a complex, attenuated structure with many masses. This in itself might not be a complete deterrent, in view of the seriousness of the basic problem; but there is also reason to believe that the iterative scheme for force adjustment will not converge if the structure has natural frequencies that are nearly equal.

Need for research: One of the necessary steps in acquiring the ability to make quantitatively accurate flutter predictions with a high degree of consistency is to accomplish certain advances in ground resonance testing. A fundamental research program is required for the development of testing equipment and new techniques. One promising line of investigation would be aimed at developing (and demonstrating by tests on structures of suitable complexity) a system with the following capabilities:

(a) To determine accurately <u>all</u> of the natural frequencies of a given structure up to the highest frequency that is likely to be of any interest for flutter, regardless of frequency spacing

(b) To excite and measure separately each of the normal modes corresponding to the pertinent natural frequencies of the structure

Although a considerable quantity of theoretical vibration data usually exists when the ground test is conducted, the test operation itself should be completely independent of these data. Purely experimental procedures should be developed for determining natural frequencies and exciting the corresponding modes; empirical criteria should be used in judging the validity of the results. The amount of test equipment should be as small as possible. The principal problem is to eliminate only those modes whose frequencies are close to that of the desired mode; hence it seems unnecessary that the excitation should be orthogonal to modes whose frequencies are more remote. This suggests the possibility of a system using fewer exciters than that proposed by Lewis and Wrisley. Consideration should also be given to the use of high-speed computers and automatic data processing equipment. Initial developmental testing might be performed on a small-scale laboratory specimen, preferably with some provision for producing variable frequency ratios. Final evaluation should be accomplished by testing several systems whose complexity approaches that of actual airplanes; perhaps scaled flutter models might be used for this purpose.

Another approach which is favored by some flutter specialists would abandon the attempt to excite normal modes, and merely seek to determine the response of the structure (both in amplitude and phase) as a function of frequency, when excited by sinusoidal forces at various points. Results of such a test would be compared directly with theoretical forced response data. It will be necessary to conduct further research in the physical basis of structural damping of practical aircraft structures in order to succeed in a program of this nature, since there is no really satisfactory theory of structural damping at the present time. Further, research is also needed on the forced response of aircraft having powered control systems, with particular attention to nonlinear effects.

Measurements to Determine Stiffness

Because of the great importance in flutter of the forces due to structural deformation, numerous attempts have been made by aircraft manufacturers to obtain a direct check of structural stiffnesses by measuring static deflections of the airframe under known loads. However, for a number of reasons to be mentioned in the following paragraphs, these efforts have been relatively unsuccessful. Nevertheless the objectives of this sort of test are extremely worth while, and it is felt that a research program is needed to develop adequate techniques for this kind of testing.

The aim should be to obtain sufficiently comprehensive flexibility or stiffness data to serve for accurate calculation of vibration modes and frequencies of the complete aircraft, up to the highest order required for flutter analysis. Initially this work might be performed at room temperature, although it should be recognized that stiffness measurements are likely to play a very important role in flutter prediction for structures which are subjected to aerodynamic heating. Therefore, it is clear that the development of techniques for stiffness measurements on heated structures is an extremely important research objective.

Since structural interaction between components has an important influence on vibration characteristics of the airplane, it is essential in making stiffness measurements that the airplane be treated as a complete entity. Obviously it must be supported in such a way that the support system does not introduce any constraints on the airframe. Deflections should be referred to a reference system attached to the aircraft.

It should be recognized that a high degree of accuracy is required in stiffness measurements which are to be used for prediction of vibration modes of moderately high order. The reason for this may be attributed to the complexity of the vibratory inertia loading, which may exhibit several reversals in direction within a single component. Because of this complexity, so-called secondary effects (transverse shear, shear lag, torsion-bending, and other effects as yet unnamed) tend to be important.

Another source of unusual difficulty arises from the fact that very large loads are required to produce measurable deflections in the stiffer parts of the structure. Perhaps the solution to this difficulty lies in the development of more sensitive instrumentation.

Hence, it is evident that the development of adequate experimental techniques for determining structural stiffnesses is an exceptionally difficult problem. In order to obtain a satisfactory solution, it seems likely that a basically new technique and/or a new system of instrumentation will have to be devised.

Oscillatory Aerodynamic Forces

Experimental values of the air forces on oscillating air forces are of primary value as a basis for evaluating the accuracy of aerodynamic theory. Although often suggested, the employment of experimental oscillatory coefficients in a flutter analysis has been seldom attempted.

As shown in figures 2(a), (b), and (c), a relatively small number of oscillatory air forces have been determined experimentally.

The greatest bulk of data existing in this field has been obtained at very low subsonic speeds and for two-dimensional airfoils. Its principal purpose has been to prove or disprove the existing theories, and it has indicated that the subsonic two-dimensional theory is quite satisfactory, where no separation is present. However, a critical lack of information exists in the transonic and supersonic speed range.

In the charts all known measurements are included. It appeared unreasonable to attempt to present charts showing all the possible variations that might be of importance in the flutter problem; instead, the air forces have been classified according to the three basic types of rigid modes of oscillation. To date there is only one known case where air forces have been measured with elastic modes.

The individual charts are divided by the parameters two-dimensional, three-dimensional, and so-called interference effects. The additional split between high and low aspect ratio has been determined for the time being by a parameter, based on aspect ratio and thickness, established in steady-state aerodynamics. It is believed that such a division is very important, particularly in the transonic case, and might allow for computations based on slender-wing theory to predict with good accuracy flutter cases in the low-aspect-ratio regions.

For high aspect ratio, it does not appear that theory will be generally satisfactory in the transonic region without considerable modification based on experimentally measured air forces, due to the increased importance of two-dimensional effects. Where some measured air forces do exist, it has been shown that relatively large changes in the air forces occur due to Mach number, angle of attack, thickness, and thickness distribution. These effects may be modified again by finite-span influences.

The interference parameter includes air forces measurements made in the presence of tip-mounted external stores and spoilers mounted on two-dimensional wings. It should include, if data were available, other interference effects such as strut-mounted and semisubmerged stores, fuselage interference (particularly in the supersonic region where wing bodies can no longer be considered separately), and the interference between horizontal and vertical stabilizers.

A special type of interference can occur supersonically on vertical or on horizontal stability surfaces created by oblique shock waves originating on the main lifting surfaces, on stores, or on other discontinuities on these main lifting surfaces. It has already been shown that these effects can be serious in stability studies. The most serious possibility is the direct aerodynamic coupling between the primary lifting surface and the stability surfaces.

The most important parameter not indicated on the charts would be angle of attack, which, if included, would be split into effects both below and above the stall region, in addition to those at zero angle of attack. In addition, all of the following items can have important effects:

(a) Airfoil section:
    Thickness
    Thickness distribution

(b) Wing plan forms:
- Aspect ratio
- Taper ratio
- Thickness taper ratio
- Fixed root
- Elastic root
- Rigid modes
- Elastic modes

(c) Wing-body combinations:
- Fuselage wing
- Primary surface on secondary surfaces
- Stores:
  - Strut mounted
  - Attached and semisubmerged

The status charts, along with the presentation of the considerable number of variables not shown by the charts, indicate an almost insurmountable amount of required future research. It is therefore desirable to discuss in some detail a proposed future research program which even in its drastically reduced nature will still require a greatly expanded effort in order to complete in time to be useful in the 1959 to 1966 design period.

The criterion used to establish the important research areas will be: Where is theory inadequate, or apparently inadequate at the present time, and where do we have clear indications that checks on supposedly adequate theory are desirable? These considerations will also define the Mach number, angle of attack, and configuration.

Inadequate theory: Subsonic-high-angle-of-attack theoretical approaches are as yet inadequate. Research already completed has indicated certain trends; primarily, however, it has been shown that the degree of instability is associated with the type of stall being encountered. It is necessary to actually measure air forces on finite-span elastic wings to obtain a more useful approach to the stall-flutter problem.

The actual plan forms recommended for investigation will be the same as those to be recommended for transonic investigations. It is possible that in a transonic facility some of the high-angle subsonic work could be conducted in conjunction with transonic investigations.

The transonic speed range is the most serious region insofar as adequate theory is concerned. Transonic pitch and translation air forces are seriously lacking for finite-span wings. There is some hope here that theoretical approaches might be developed for slender wings, as was indicated in the discussion of the status charts. It appears desirable to begin this research with a series of affinely related rectangular wings, as has been done for the static-aerodynamic case. These wings should be oscillated in elastic modes. It should be pointed out that, although shaking models in elastic modes presents a research technique problem, it is, as a matter of fact, as difficult to oscillate three-dimensional wings in rigid modes because of the always present elastic components which can cause extreme difficulty in evaluating results. In all cases air forces should be obtained, at a minimum of three-spanwise stations, and the overall integrated air forces should be measured. The following parameters should be investigated:

(a) Aspect ratio - 1 to 6

(b) Thickness, insofar as structurally feasible, from 2 percent to 6 percent

With the above basic test completed, checks on effect of airfoil shape should be made in the slender-wing or low-aspect-ratio region and in the high-aspect-ratio region. The research should then proceed to investigate plan-form effects, such as taper ratio and sweep, including delta plan forms. It is again recommended that insofar as possible and practical the research be conducted using controlled elastic mode shapes.

As pointed out previously, of all the transonic problems, those involving control-rotation air forces, for example, "buzz," are responsible for more serious flutter problems than from any other single parameter. A need exists because of our inability to predict with any degree of reliability the deterioration in damping encountered in this speed range. The primary variables requiring investigation are:

(a) Control chord, in percent of wing chord

(b) Effect of aerodynamic balance

(c) Type of aerodynamic balance

(d) Spanwise effects

(e) Control contour, including airfoil shape ahead of control

(f) Percent of wing span

(g) Spanwise control location

(h) Effect of wing plan form

A program set up to investigate all of the above factors and their effects on each other would be impossible to complete in any reasonable time; however, it is believed that by proper techniques many basic principles can be uncovered. This technique should involve the measurement of air forces at several spanwise stations in addition to measuring the complete integrated air forces. In addition, it is vitally important that as principles are uncovered, every effort should be made to investigate methods of increasing the control damping.

Adequate theory does not exist in any speed range that can account for all possible interference effects. These interference problems were mentioned in discussing the status charts and to some extent in the previous discussions concerning specific speed ranges. Stores must be considered a primary problem, and it is recommended that representative stores be designed for installation on a number of the three-dimensional models. These stores would be typical installations, and the speed ranges should be those in which the configuration would be expected to fly.

The other types of interference such as spoilers and speed brakes should also be checked on representative wings built for fundamental research.

Work of this type would be aimed at obtaining generalized results in order to reduce the magnitude of the job as much as possible.

Since the research work must be aimed at generalized results, it would be highly desirable to develop and publish techniques that would permit rapid evaluation of specific airplane configurations by model tests.

Adequate theory: There is some reason to believe that supersonic theory will be satisfactory except in the Mach number region near shock attachment and for secondary problems of separation. The separation problem which is not accounted for in any existing theories will tend to increase with increasing Mach number, and checks on the percent deviation from theory will be desirable. Controls of the trailing-edge type would be most seriously affected by separation. Another problem exists in the region of shock attachment, since wing oscillation might detach a statically attached shock, and the possibility of recurring detachment is immediately apparent, and this would be difficult to treat theoretically. Of course, the complete wing and all its air forces will be affected by the possible shock detachment problem.

The specific type of research will be limited by available facilities, particularly in the Mach number 3 to 5 region. It is recommended that two-dimensional work which could be conducted in relatively small research facilities be performed to obtain a preliminary evaluation of theory. The variables to be investigated would be airfoil section and thickness and controls. In the higher supersonic Mach number ranges this work will be of considerable value since more of the wing acts in a purely two-dimensional manner. The results of preliminary tests would have to be evaluated to determine the amount of additional two-dimensional work that would be desirable.

It is also desirable to investigate concurrently with the two-dimensional work some representative three-dimensional wings in order to obtain reliable checks of the usefulness of two-dimensional research. In addition, it can be expected that three-dimensional elastic wings can develop special problems due to the expected spanwise variation in separation and shock attachment when oscillating in elastic modes. These particular problems in themselves dictate the necessity for conducting three-dimensional elastic model research on typical plan forms.

Sufficient data: The problem that has been discussed is not specific concerning the magnitude of the research. It is, of course, necessary for the research agency to detail the programs based on the type of facility involved and the amount and type of manpower available. Maintaining the present level of effort during the next 5 to 10 years will not approach solving the problems that have been outlined. This is obvious from the status charts, which indicate the availability of all known transonic and supersonic air forces obtained in the last 10 years. It is immediately apparent that the present level of effort must be increased several times in order to make significant progress in the present and future critical period.

Flutter Models

The purposes of flutter model tests include, among other items, the following:

(a) Aircraft structural integrity determination

(b) Mach number and dynamic pressure trends in terms of velocity-stiffness indices $\left(\frac{b\omega_\alpha}{a}\sqrt{\frac{\mu}{\mu_o}} \text{ versus } M, \text{ and } \frac{V}{b\omega_\alpha\sqrt{\mu}} \text{ versus } M\right)$ to define the critical regions

(c) The flutter susceptibility of various new design configurations, the critical modes and corresponding flutter prevention design criteria

(d) Evaluation of analytical flutter prediction techniques and of need for improvements in flutter prediction theories

(e) Determination of generalized flutter forces (derivatives) from systematically conducted tests

(f) Optimum design from a flutter viewpoint and flutter prevention means

A brief evaluation of recent tests appears to indicate that the emphasis is being placed on the first three items. Although significant man-hours are being devoted to item (d) above, additional emphasis in this area is needed. In many cases, flutter model speeds are compared with reference flutter velocities derived from simple analyses which employ two-dimensional, incompressible flutter derivatives even though the effects of aspect ratio and compressibility are significant. It is considered advisable to seriously consider the use of a better reference flutter speed which is based on more accurate theoretical or semirational procedures which reasonably account for spanwise and chordwise loadings. Although additional time will be necessary to introduce more elaborate reference analyses, it is estimated that a major payoff will occur through a significant reduction in the scope of expensive flutter model tests where, in general, an ad hoc experimental approach is employed. A better basic understanding of the flutter mechanism can conceivably be obtained by improved analyses not only in the form of velocity but also in terms of margin of stability or damping g. The reasons for mild and violent modes might be more clearly understood.

The last item under (f) deserves special mention. In view of the increase in flutter problems and problem areas, it appears that research in this area, which has been neglected to a large extent, should definitely be emphasized and pursued.

Brief mention might be made of the desirability of standardization of flutter symbols in presenting flutter data.

Status of experimental flutter model data: The status of presently available information is summarized in table IV. This evaluation is made from the viewpoint of the practicing flutter engineer who is concerned with fairly direct applicability of available data. For some types of configurations the information is generally adequate. However, it appears that almost all areas require evaluation and consolidation of information. More data of velocity index type $\frac{b\omega_\alpha}{a}\sqrt{\frac{\mu}{\mu_o}}$ or $\frac{V}{b\omega_\alpha\sqrt{\mu}}$ versus Mach number are needed to define the critical dynamic pressure and Mach number regions. For some configurations additional data are needed to indicate the effects of fuselage flexibilities and body freedom on the flutter modes. These motions are especially important for wings with stores and may be fairly significant (in terms of flutter velocity and damping margins of safety) even for clean wings.

The areas requiring particular attention at the present time appear to be:

(a) Mass unbalanced conventional control surfaces

(b) T-tails

(c) Control-surface buzz

(d) All-movable control surfaces

(e) Wings with stores

In addition, the thinner surfaces proposed for supersonic speed ranges require additional data for Mach numbers above 2.5.

Comparison of model and aircraft results: Unfortunately, there are very few cases where model and aircraft data are both available to assess the accuracy of model testing techniques. Two recent cases are known. One case involved a bomber with pylon suspended engine where the model incorporated fuselage flexibilities and freedoms. If the model results were used directly without prior knowledge of the aircraft results, it is quite probable that the aircraft flutter speed predicted on the basis of the model results would have been about 10 percent unconservative. Compressibility effects are negligible in this particular case. In another case involving a bomber with several external stores (pylon suspended engines), the low-speed model results taken at face value predicted flutter stability although low damping in some modes was indicated, and the flutter speed in other modes was just above the limit dive speed. The airplane fluttered in a higher-order wing mode which was not predicted by initial model tests. Thus, in this particular case the model was also unconservative.

Additional comments could be made by comparison of model and aircraft results if g - v data for the critical modes were available. Since full-scale flutter flight tests where actual flutter conditions are encountered will likely not be permitted except possibly by a near approach to flutter, it appears highly desirable to obtain model amplitude versus frequency response data at several airspeeds to compare with corresponding aircraft data.

Thus, the few cases for which data are available indicate that model results can be unconservative. However, sufficient data are not available to draw fairly firm conclusions regarding general flutter model accuracy. These additional data are urgently needed and should be obtained. Overconservatism is not desired because of other penalties (weight, performance, etc.) but, on the other hand, unconservatism cannot be tolerated in view of the risks involved.

Model simulation: For models that can be represented by a spar type of construction, it may be possible to simulate the specified (not aircraft) stiffness characteristics to approximately 5 percent. In more complicated structures where an influence coefficient approach is necessary, an accuracy of better than 10 percent can probably not be obtained. The above comments pertain to models that are tested in high-density environments since it is extremely difficult to simulate large, low load-factor aircraft by means of small models tested in low-density facilities. Aircraft flutter models should generally be as large as possible and should be tested in as high a density facility as is practical.

Mass simulation (weight, center of gravity, and moment of inertia) presents a problem and must be strictly controlled especially where several similar models are used and repetition of parameter accuracy is necessary. Mass control to a large extent is experimental and may not be guaranteed as closely as stiffnesses.

In general, model stiffness simulation appears to proceed along the following lines. An evaluation of the stiffness distribution of the aircraft is made. A similar or equivalent (not necessarily a replica) duplication is made of structural elements. If the aircraft structure approximates plate characteristics, then a plate-like structure will have to be employed and the usual "beamology" approach must be discarded. Since the above approach will not generally simulate local stiffnesses and since accurate duplication of influence coefficients is not possible at this time, the higher-order modes and frequencies on flutter models will probably not be sufficiently similar to those of the aircraft and the model will probably not yield sufficiently accurate results for these particular modes. This problem area should be resolved since the thinner surfaces of future supersonic and hypersonic aircraft may result in the occurrence of higher-order flutter modes.

Effort in the simulation of actuators and dampers is also needed.

Model support: In testing of low-speed flutter models which incorporate body freedoms, many contractors have encountered body-freedom-type instabilities. Most of these instabilities were solved by essentially cut-and-try methods. One case is known where the body instability could not be prevented even with a very forward center of gravity.

In general, it appears desirable to incorporate body freedoms and fuselage motions in flutter models even for clean wing models to approximate root impedance effects.

For supersonic and transonic tests, it does not seem desirable to fly models but rather to restrain the model with approximately correct root effects. Trim surfaces to provide attitude control may be required.

The general area of model support techniques and their possible body instabilities deserves further study and evaluation.

Component versus complete aircraft model testing: Wherever possible, the entire aircraft including rigid body freedoms should be modeled especially on subsonic models where it is more practical to do. Such low-speed tests can be employed to determine the desirability and accuracy of component testing by locking out or restraining modes of motion.

The effect of fuselage degrees of freedom or body motions is probably quite important for wings with stores, T-tails, and all-movable control surfaces. Body impedance characteristics should therefore be simulated or approximated. Body modes and fuselage degrees of freedom may influence even clean wing flutter results and some tests should be made to determine fuselage effects to provide aircraft designers with a basis of evaluation for cantilever tests.

Model tests are considered necessary to evaluate the advisability and accuracy of component testing and to determine the effect of fuselage freedoms on cantilever tests.

Simulation of liquid fuel: The similarity rules necessary for reproducing liquid fuel effects in models should be investigated if such an investigation is not already available in the literature.

It appears possible to simulate viscous effects if a 1:1 velocity ratio and a high-density facility are employed since then the Reynolds number would be high. However, simulation of other dimensional parameters such as the Froude number which is related to fuel wave length may be necessary.

Simulation of fluid effects by means of model tests in low-density facilities does not appear feasible.

Excitation and instrumentation: The importance of defining flutter modes in experimental tests is realized. Vibration measuring equipment is generally available for the larger flutter models. Strain-gage equipment can be used for obtaining data which can be employed for determining modes of small models. However, small, lightweight accelerometers are needed to define amplitudes at strategic locations and boundary condition information for strain-gage intelligence.

For wind tunnels having high-turbulence levels, no forced excitation may be necessary for general flutter research. However, amplitude versus frequency data at various airspeeds may be required in certain tests to evaluate marginally stable modes of more complex model investigations. Some research to develop suitable methods especially for small models is considered advisable.

Temperature: Models which are constructed to be tested in an environment which simulates temperature effects will probably consist entirely of metal construction. They therefore will be heavy. In view of the present difficulty of simulating weight for small models, it may be impossible to construct a dynamically similar thermoaeroelastic model for testing in heated supersonic wind tunnels unless these tunnels operate at very high densities. If such high-density tunnels were available, transient as well as steady-state temperature effects could conceivably be obtained by injecting "cold" models.

Other facilities which could be employed for thermoaeroelastic studies are free-rocket and sled-rocket facilities. However, it appears possible that a geometric scale ratio of less than one even for a replica (scaled down, bit by bit reproduction) type model will not simulate heat transfer and temperature effects. It also appears possible that trajectory limitations for a rocket test may prevent attaining the proper speed-altitude-Mach number - dynamic pressure parameters necessary for simulating temperature effects of an airplane in its own speed-altitude environment.

Since the simulation rules for thermoaeroelastic models are not available in the literature at this time, it is considered very worth while to publish a report on this area. This report should evaluate the possibilities of thermal simulation in flutter model testing using presently available and proposed facilities.

Facilities: Wind-tunnel, free-rocket, and rocket-sled facilities exist for testing of flutter models (temperature effects not included). Sufficient low-speed wind tunnels are available for the preliminary subsonic tests that are generally conducted by the contractors. However, in view of the state-of-the-art and in view of the lower margins of safety, airplane and missile contractors must conduct transonic and supersonic model tests on a research and development basis. Additional transonic and supersonic wind-tunnel time or wind tunnels are needed to provide both research and development flutter information. Such tunnels should be preferably of the higher-density type.

The sled facility is considered to be an excellent facility for go or no-go flutter tests of moderately sized aircraft components. However, its control and expense make it a less desirable test facility than a wind tunnel. Its utility for those tests for which it is especially qualified is well known and appreciated.

Rocket-model tests are also quite expensive and are a one-shot proposition although recoverable rocket procedures could be developed. In many cases rocket tests must be employed, especially where the speed range of available wind tunnels is not sufficient or where aircraft parameters cannot be simulated. However, in general, the free-rocket testing procedure is less desirable if suitable wind tunnels are available, since more information can generally be obtained quicker and cheaper in the wind tunnel. However, rocket tests should be made frequently to substantiate the flutter data obtained by wind-tunnel tests.

The sled facilities appear sufficient at the present time but increased use, for example, temperature investigations, may require additional availability (hours) or facilities. Similar comments apply to the free-rocket tests except that flutter demands on this type of facility will likely increase in view of lack of wind-tunnel facilities in the high supersonic speed range.

Should a similarity-rule study and an evaluation substantiate the possibility of using heated wind tunnels for thermoaeroelastic studies, the single wind tunnel being considered by the NACA will not likely be sufficient unless a high percentage of time is devoted to flutter research. More facilities of this type may therefore be necessary. In addition, serious consideration should be given to need for flutter research facilities for the Mach number range above 3.

Flight Flutter Testing

The increasing importance of flight flutter testing as a branch of flutter engineering has been mentioned earlier in the report, but a brief recapitulation of the underlying reasons is of value.

As airplane and missile performance increases, and as new speed and temperature regimes are entered into, it appears certain that design difficulties from the flutter point of view will become more severe. Moreover, problems of design-office flutter prediction will also increase as a consequence of the growing complexity of the airborne vehicle and its missions. To insure that an adequate safety margin for flutter truly exists in a new model, more and more dependence will probably be placed on proof flight tests, that is, on flight flutter testing of the prototype aircraft, in the same sense that performance and flight load proof tests are now undertaken.

In addition to providing an estimate of the flutter safety margin, flight flutter testing is also an important research and development tool. Through such studies, the nature of the flutter modes on actual aircraft can be identified, their stability in the region immediately below the flutter speed can be appraised (serving as a firm basis for extrapolating to the flutter condition), and research information can be gained regarding the mechanical and aerodynamic counterparts of the flutter mechanism.

While some flight flutter testing has been undertaken by industry in the past, particularly when studying mild flutter modes associated with control surfaces, it is probably correct to say that our knowledge of the techniques for this type testing are woefully inadequate. Stated differently, if the premise is accepted that flight flutter testing is an increasingly important research and engineering tool, then the conclusion must be drawn that our present status of knowledge is at least an order of magnitude behind our requirements.

When considering flight flutter testing as an engineering tool, the question of its safety at once arises. For studies of mild flutter modes, it is of interest to note that at least one aircraft company displays no hesitation whatever about flying a new model near the flutter speed. On the other hand, the dangers of an improperly conducted flight flutter program are well illustrated by the classic von Schlippe tests, in which a bending-torsion wing mode was approached (and probably reached) with catastrophic results.

Proponents of flight flutter testing have recently suggested certain new and promising experimental approaches. They point out that artifical stability of known magnitude can be added to the system. (This is particularly simple when dealing with movable elements such as control surfaces.) By this technique, the flutter speed of the vehicle can be readily controlled and raised, perhaps even to the extent of converting a violent (catastrophic) mode into one of the mild variety. Flight tests can then be conducted safely at relatively high speeds, covering the flutter regime for the unmodified system; by studying the flight test data and subtracting analytically the effect of the artificially added stability, the performance of the unmodified vehicle can be deduced.

The procedure of controlling the system stability by artificial means, if successful, will obviously be a major step forward in improving the safety of flight flutter testing. To date, experience in this direction is limited to only a few trials, and these only with mild tail-surface modes.

The instrumentation for flight flutter testing is, in principle, of a relatively straightforward nature, but considerable difficulties are encountered in obtaining suitable and useful flight flutter data. Both sinusoidal or pulse-type excitations have been employed, and difficulty is realized in both cases in achieving suitably large (though not dangerous) aircraft responses in regions of low-to-moderate stability. Both types of excitation have their particular advantages, the pulse-type exciter being the least expensive to install (in some cases the "stick-banging" technique is employed), while the sinusoidal exciter probably affords the more reliable overall information.

Other instrumentation problems of flight flutter testing include the isolation of the aircraft response to forced vibration from the random and uncontrolled responses which accompany flight in rough air. The problems of achieving accuracy in the reduction of flight data are obviously connected with the signal-to-noise ratio of the recorded data, and practical means are required to permit reducing flight data when this ratio is small. It must be appreciated that unless accuracy can be achieved in the flight observations in regions of low-to-moderate damping, then planning of the flight tests into areas near the flutter speed becomes both difficult and uncertain.

It should also be mentioned that further research is required to yield a better understanding of the basic dynamical considerations involved in flight flutter testing. Thus, when sinusoidal excitation is employed, it is conventional to sweep a frequency range, while attempting to measure the response versus frequency characteristics for a test speed and altitude. It is known that the sweep rate of the exciter will distort somewhat the nature of the records obtained, and in most cases the speed and altitude will be continually varying. For high-speed testing, particularly where the times available for a test run are small, it is obvious that interpretations of the flight data must be considered carefully. It is also clear that great importance is attached to an early identification of the violence of an approaching mode. These are but typical problems requiring clarification, and are representative of the type of dynamic research needed to strengthen our understanding of flight flutter techniques.

While every effort is being made in this report not to overexaggerate the research requirements of the flutter engineering area, it can be stated without hesitation that a systematic research program on flight flutter testing is an absolute necessity for the near future. This test technique, because of its importance in future design, must be developed to the point where it is both fruitful and safe. A coordinated flight research and theoretical program, aimed at studying the performance of aircraft displaying typical flutter modes, is probably the only manner in which the safety question and other pertinent matters can be clarified.

SUMMARIZATION

This survey and evaluation of flutter research and engineering attempts to appraise the present status of the "state-of-the-art," and suggests areas in which research is required to close gaps in our existing design knowledge. In order to somewhat circumscribe the coverage of the report, principal consideration is given to the matters relating to fixed surfaces and primary controls. A listing of the more important items discussed in detail in the survey is as follows:

1. A historical analysis of actual flutter occurrences during the last 10 years experienced with U. S. military aircraft reveals at least 54 known cases. The consequences of flutter in these instances range from complete loss of the aircraft to moderately severe structural damage;

this in turn has resulted in delays in readying the vehicle for service operation (in some cases up to 6 months), considerable expense in correcting the difficulties, as well as increased maintenance and/or decreased performance for some of the vehicles. This flutter history indicates that present design criteria are not completely adequate to cope with flutter design problems.

On future airborne vehicles, the design demands of higher performance and new configurations may well lead to an increase in the number of flutter occurrences, unless adequate design tools for their prevention are provided. This implies that research effort in the flutter field must be expanded considerably if this objective is to be met.

2. Our present understanding of the dynamics of flutter is in some respects reasonably adequate, although many important questions are still not thoroughly understood. For example, simple and dependable methods for predicting whether a flutter mode is of the catastrophic or mild variety are not yet available, and few general rules are available to serve as a basis for the synthesis of optimum flutter-free aircraft systems. Only a beginning has been made toward understanding the complications introduced by high-speed flight in regions where thermal effects are important.

3. As a first step in a theoretical flutter analysis, the flutter engineer will usually calculate the pertinent natural frequencies and normal vibration mode shapes of the airframe in still air. These are not only useful for the subsequent calculation of critical velocities, but are also employed for comparison with ground vibration tests; this latter comparison affords a valuable check on the engineer's understanding of the mechanical properties (inertial and structural) of the system.

While present techniques for calculating normal modes are reasonably successful for conventional aircraft of not too low aspect ratio, they are generally inadequate for the handling of very low-aspect-ratio aircraft, and large aircraft of flexible nature and carrying a variety of flexibly mounted components and external stores.

Rational methods are not presently available for estimating the damping associated with vibratory aircraft motions, such information generally being obtained experimentally from the ground vibration test. This purely experimental treatment of the damping parameters (which may be of considerable importance in fixing the critical flutter speeds), does not completely satisfy design requirements.

Further study is required to improve current techniques for natural mode studies, both from the theoretical and experimental points of view. It is suggested that a systematic analytical and experimental study, employing representative full-scale vehicles, be used as a basis for refinement of our knowledge in this area.

4. The present status of knowledge in regard to the analytical computation of oscillatory aerodynamic flutter forces is excellent in some areas and lacking in others. Two-dimensional potential flow methods are reasonably well developed with only few exceptions; however, three-dimensional potential flow methods are in a continuing state of flux and are currently being defined and evaluated.

The two-dimensional methods have been very useful in studies for large-aspect-ratio surfaces, and it appears that further research in this area should be confined to studies relating to special mode patterns, such as those involving airfoil camber, and to studies of certain control-surface problems, such as buzz.

Considerable additional research is required in connection with three-dimensional potential flow methods, which methods are badly needed by industry for the design of low-aspect-ratio wings and wing-body combinations. In this area, it appears necessary that multiple lifting-line methods be employed, or that lifting-surface methods be used, these being readily applicable to the treatment of elastic vibration modes of a general character.

Greater emphasis is also needed on studies of thickness effects at high supersonic speeds, and on the use of indicial functions as a flutter tool. Attention should also be given to the development of additional theories which account for viscous flow effects, such as separation.

5. The available numerical methods for calculating critical velocities from the equations of motion are reasonably adequate, and research along these lines is progressing at a satisfactory rate. However, the problems of evaluating the accuracy of a flutter analysis are still formidable, and the precision of flutter analyses for unconventional configurations is still open to considerable question. Better understanding is required of the roles played by the mechanical and aerodynamic characteristics of the airframe in the final flutter determination. The effects of the various temperature regimes on flutter are understood in very preliminary fashion only.

6. Current methods of ground vibration testing are reasonably satisfactory only when low-order vibration modes are of interest, and when the natural frequencies are well separated. Because of the increasing complexity of modern airborne vehicles, and the need for greater quantitative accuracy in flutter prediction, difficulty is being experienced in maintaining adequate ground vibration test accuracies. Additional research effort is therefore required to develop ground vibration techniques and test equipment which is capable of exciting and measuring all of the natural vibration modes of complex airborne vehicles.

7. Attempts to determine structural stiffnesses of airborne vehicle structures by measurements of static deflections under known loads have been relatively unsuccessful due to the severe accuracy requirements. Present and future importance of the problem suggests that a substantial research effort be directed toward the development of adequate techniques and equipment for obtaining the required stiffness data. Attention must be given to both unheated and heated structures.

8. An examination of available experimental data on oscillatory air forces shows that this information is lagging considerably behind current needs, let alone future needs. Most of the experimental work has been done in connection with two-dimensional wings in the subsonic speed range, and on rigid models. Only one piece of data exists for an elastic model. A critical lack of experimental information exists in the transonic and supersonic speed ranges, even for rigid models.

The greatest need for future research lies in the measurement of oscillatory air forces and oscillatory pressure distributions on three-dimensional elastic models (incorporating both fixed surfaces and movable surfaces) in all speed regimes. These measurements should show the results of flow separation and interference effects, particularly in the transonic and supersonic speed regimes. There is need for further research on two-dimensional wings to check theory; this applies particularly in the subsonic speed region at high angles of attack, at transonic speeds, and at supersonic speeds.

9. The use of flutter models, up to the present, has been for the primary purpose of checking aircraft safety, as well as for limited research objectives. For certain configurations, flutter models have been used to define Mach number and dynamic pressure trends as a function of flutter velocity-stiffness indices, and for the determination of the flutter susceptibility of various new designs. For a variety of configurations of practical interest, however, adequate flutter model studies to provide design criteria and for comparison with theoretical calculations are not available.

The systematic use of flutter models as a basis for evaluating the accuracy of proposed flutter prediction theories is a technique which has not been employed to maximum advantage in the past; such studies would undoubtedly also bring to light directions for the improvement of existing theory. Also, the use of model studies for the synthesis of optimum flutter-free systems, and for the study of various flutter prevention techniques has also not progressed as rapidly as might be desired.

There appears to be a definite need for consolidation and evaluation of available experimental data, and for extending and filling in gaps in existing data for various configurations, with regard to critical regions from the Mach number and dynamic pressure standpoint. The simulation of higher-order vibration modes in flutter models, of liquid fuel effects, and of the effects of various temperature regimes also require further study before acceptable techniques can be integrated into design practice.

Another continuing area of uncertainty in the conduct of flutter model tests relates to the necessity of testing complete models of an airborne vehicle, as compared with the less expensive testing of components only, in which only a part of the airframe is duplicated (it being assumed that the remainder of the structure does not significantly participate in the flutter motion). The accuracy and validity of component testing requires further delineation.

In addition to overall questions relating to the use of flutter models, certain problems of flutter model construction and mounting require solution. These include problems of mounting models simulating free flight in the wind tunnel, the development of improved model excitation techniques, lightweight vibration measuring equipment, techniques of model construction, and the provision of adequate facilities for high-speed and thermal regime investigations.

10. It is the opinion of those preparing this report that flight flutter testing will be an increasingly important branch of flutter engineering in the future. Because of the difficulties associated with the theoretical treatment of aircraft configurations of increasing complexity, greater emphasis will have to be placed on flight testing of prototype articles in order to insure that adequate flutter safety margins exist. In addition to its importance as a design tool, flight flutter tests will probably be used for a variety of flutter research purposes.

Current flight flutter test techniques are in an early stage of development, and are beset with a number of practical difficulties pertaining to safety, instrumentation, and data reduction and interpretations. Both theoretical and experimental research is urgently needed to gain experience and knowledge for flight flutter testing, as a preliminary to the increased utilization of this technique within the industry.

A promising means for increasing the safety and utility of flight flutter testing appears to be the introduction of controlled artificial stability into the aircraft flutter system. Exploration of the flutter characteristics over the range of anticipated flutter velocities can then be undertaken without danger, the test data then being reduced by subtraction of the added artificial stability to yield the accurate flutter speeds of the unstabilized airframe.

While a variety of theoretical and practical questions require further clarification, the future importance of flight flutter testing should not be overlooked, and research should be instigated at the earliest possible date to develop this form of prototype testing.

TABLE I.- SUMMARY OF FLUTTER INCIDENTS

Type of flutter	Year											
	1947	1948	1949	1950	1951	Total 1947 to 1951	1952	1953	1954	1955 to 1956	Total 1952 to 1956	Grand total
Trim tab flutter	2	1		1		4	2	1	1		4	8
Mass balanced spoiler oscillations	1					1						1
Stabilizer second bending statically balanced elevator flutter	1					1						1
Stabilizer (fin) first bending statically balanced elevator (rudder) flutter		1				1		1			1	2
Straight wing with tip tank flutter			1			1	1	1			2	3
Fuselage side bending-rudder rotation-autopilot flutter			1			1						1
Fuselage bending statically balanced rudder (elevator) flutter				2		2						2
Stabilizer torsion mass unbalanced elevator flutter				1		1						1
Mass balanced spring tab flutter					1	1	1				1	2
Straight wing with tip tanks (asymmetrically loaded) flutter							2				2	2
Control-surface buzz							5	4	5	5	19	19
T-tail flutter							1				1	1
Control-surface buzz flutter										1	1	1
All-movable stabilizer flutter								1(1)		3	4	4
Swept wing with external stores (both pylon suspended and no pylon) flutter									1	1	2	2
Unbalanced or partially balanced control surfaces								1(2)		1(3)	2	2
Fin bending torsion										1	1	1
Tab buzz										1	1	1
Total	4	2	2	4	1	13	12	9	7	13	41	54

Note: If several cases of the same type of flutter occurred on the same aircraft, it is reported as one case.

(1) Full-scale sled test.

(2) Flutter occurred subsequent to failure of elevator torque tube producing a free, partially balanced, control surface.

(3) Flutter occurred subsequent to loss of aileron servo system producing a free, partially balanced, control surface.

TABLE II.- AVAILABLE THEORETICAL OSCILLATORY AERODYNAMIC FORCES

[Based on two-dimensional linearized subsonic and supersonic flow theory]

Source	Authors	Title	Range of parameters and remarks
AF Tech, Rep. 4798	Smilg, B., and Wasserman, L. S.	Application of Three Dimensional Flutter Theory to Aircraft Structures	$1/k = 0$(irregular) 16.67; $e = -0.5(0.1) + 0.7$
AAF Translation Rep. No. F-TS-599-RE	Schwarz ZWB,FB1838 (1943)	Tables for the Calculation of Air Forces of the Vibrating Wing in Compressible Plane Subsonic Flow - 1946	$M = 0$ to 0.9 in steps of 0.1; $z = k(x - x_o)$ from 0(0.02) 2.0 approximately
AAF Translation No. F-TS-948-RE German ZWB, FB 1773	Dietze, F. (1943)	The Air Forces of the Harmonically Vibrating Wing in a Compressible Medium at Subsonic Velocity. Part II Numerical Tables and Curves	$M = 0$, 0.5, 0.6, and 0.7 Few k values
Aeronautical Research Council 9506	Schade	The Numerical Solution of Possio's Integral Equation for an Oscillating Aerofoil in a Two-Dimensional Subsonic Stream (Translated by S. Skan) - Part III	$M = 0$ to 0.9; $k = 0$ to 1.0
Structures D.5/7501/I.T.M./5	Dietze, Frazer, and Schade	Tables and Curves for Two-Dimensional Subsonic Aerodynamic Derivatives	
NACA TN 2213	Turner, M. J., and Rabinowitz, S.	Aerodynamic Coefficients for an Oscillating Airfoil With Hinged Flap, With Tables for a Mach Number of 0.7	$\omega_r = 0.02(0.02)$ 0.10(0.1) and 0.7 chord ratio $\tau_R = 0.15$, 0.24, 0.33, and 0.42
Royal Aircraft Establishment Rep. No. Structures 87	Minhinnick, I. T.	Subsonic Aerodynamic Flutter Derivatives for Wings and Control Surfaces	Wing $M = 0$, 0.5, 0.6, 0.7, and 0.8; $k = 0.02$(varies) 2.5. Control surface $M = 0$, 0.5, 0.6, and 0.7 chord ratio $e_\beta = 0.15$, 0.24, 0.33, and 0.42. Control surface $M = 0$, 0.7 $E_\beta = 0.02(0.02)$ 0.10(0.05) and 0.50
RAE Report No. Structures 86 (1951)	Minhinnick, I. T.	Tables of Functions for Evaluation of Wing and Control Surface Flutter Derivatives for Incompressible Flow	
U. S. Air Force Tech. Report 6688. Also AFTR 6688 - Supplement 1	Fettis, H. E.	Tables of Lift and Moment Coefficients for an Oscillating Wing-Aileron Combination in Two-Dimensional Subsonic Flow	$M = \lambda = 0.7$; $k = \omega = 0.04(0.04)$ and 0.52; $e = 0.5$; $e = 0.2(0.1)$ and 0.9
RAE Report No. Aero. 2449	Neumark, S.	Two-Dimensional Theory of Oscillating Aerofoils With Application to Stability Derivatives	
RAE Report No. Structures 142	Templeton, H.	The Technique of Flutter Calculations. Aerodynamic Derivatives for a Wing-Aileron-Tab System for Two-Dimensional Incompressible Flow	ϕ_n for $-\cos\phi$; $-0.2(0.1)$ 1.0 $E_a = 0.1(0.05)$ and 0.6; $E_t = 0(0.01)$ and 0.1

TABLE II.- AVAILABLE THEORETICAL OSCILLATORY AERODYNAMIC FORCES - Continued

[Based on two-dimensional linearized subsonic and supersonic flow theory]

Source	Authors	Title	Range of parameters and remarks
Royal Institute of Tech Stockholm, KTH-Aero TN 31	Merbt, H., and Landahl, M.	The Oscillating Wing of Low Aspect Ratio. Results and Tables of Auxiliary Functions	
NAVAER SM-39		Tables for the Calculation of Aerodynamic Coefficients of an Oscillating Airfoil Flap System in an Incompressible Fluid	$c = -0.2(0.1) + 0.7$; $1/k = 0(0.2)\ 8.0$ Values for $R_{a\alpha}$, R_{ch}, etc.
NACA TN 2739	Mazelsky, B., and Drischler, J. A.	Numerical Determination of Indicial Lift and Moment Functions for a Two-Dimensional Sinking and Pitching Airfoil at Mach Numbers 0.5 and 0.6	$k = 0(0.02)\ 0.1(0.1)\ 1.0$
National Aeronautical Research Inst. Amsterdam Rep. F.151		Tables of Aerodynamic Coefficients for an Oscillating Wing-Flap System	$M = \beta = 0.35$, 0.5, 0.6, 0.7, and 0.8 Ratio of flap to wing chord $\tau = 0.1$, 0.2, and 0.3; $\omega = k = 0(0.02)\ 1.0$
Chance Vought Aircraft Report No. 8242	Head, A. L., Jr.	A Compilation of Two-Dimensional Aerodynamic Coefficients With a Review of Flutter Analysis Methods	$M = 0$, 0.5, 0.6, 0.7, and 0.8; $k = 0$ -2.0 Supersonic from NACA TR 846
National Aeronautical Research Institute, Amsterdam Rep. F155	de Jager, E. M.	Tables of Aerodynamic Aileron Coefficients for an Oscillating Wing-Aileron System in Subsonic Compressible Flow	$M = 0$ to 0.8
J. Aero Sci. vol. 21, July 1954	Timman, R., van de Vooren, A. I., and Greidanus, J. H.	Aerodynamic Coefficients of an Oscillating Airfoil in Two-Dimensional Subsonic Flow (corrected values to J. Aero. Sci. 18, 717-802 (1951)	$M = \beta = 0.35$, 0.5, 0.6, 0.7, and 0.8
J. Aero. Sci. vol. 18, July 1951	Luke, Y. L., and Dengler, M. A.	Tables of the Theodorsen Circulation Function for Generalized Motion $(Cpe^{i\theta})$	$p = 0$(varies) 10.0; $\theta = -5^{\circ}(5^{\circ})30^{\circ}$
J. Aero Sci. vol 20, July 1953	Luke, Y. L., and Uffort, D.	A Table of the Complete Cicala Function	
Forschungsbericht Nr 1417	Borkman and Dietze	Tables on Lift Theory of the Harmonically Vibrating Wing	
NACA TN 2562, TN 2613	Mazelsky, B.	Numerical Determination of Indicial Lift of a Two-Dimensional Airfoil at Subsonic Mach Numbers From Oscillatory Lift Coefficients With Numerical Calculations for $M = 0.7$ (Pitching and Sinking Airfoil)	
Glenn L. Martin Co. Rep. ER 7734	Jordan, P. F.	Series Developments of Two-Dimensional Flutter Coefficients for Transonic and Supersonic Flow	$M = 1$ to 10(12 values); $k = 0$ to 1.5(continuous)
RAE Rep. Structures 141	Jordan, P. F.	Aerodynamic Flutter Coefficients for Subsonic, Sonic and Supersonic Flow	$M = 0$ to 2; $k = 0(0.025)\ 0.2(0.05)\ 0.7$

TABLE II.- AVAILABLE THEORETICAL OSCILLATORY AERODYNAMIC FORCES - Continued

[Based on two-dimensional linearized subsonic and supersonic flow theory]

Source	Authors	Title	Range of parameters and remarks
British R & M [illegible] ARC Tech. Rep. 8583	Temple and Jahn, H. A.	Flutter at Supersonic Speeds, Derivative Coefficients for a Thin Aerofoil at Zero Incidence April 1945	$M = 1.2$, $y = 0(1)\ 9$; $M = 1.4$, $y = 0(1)\ 6$; $M = 1.6$, $y = 0(1)\ 3$; $M = 2.0$, $y = 0(1)\ 2$; $y = \omega = \lambda M^2/M^2 - 1$ ($\lambda = 2k$) Values of l_z, $l_{\dot{z}}$, l_α, $l_{\dot{\alpha}}$, and m's
NACA Report 846	Garrick, I. E., and Rubinow, S. I.	Flutter and Oscillating Airforce Calculations for an Airfoil in a Two-Dimensional Supersonic Flow 1946	$M = 10/9$, 10/8, 10/7, 10/6, 2, and 2.5; $x_1 = 0.1(0.1)$ and 0.9; $\omega = 0.02$(irregular) 20
Curtiss Wright Corp. Report R46-1	Keller, E. G., Komm, H., and Johnson, S.	Supersonic Flight Formulae and Tables. (Bumble Bee Report 1946)	$M = 1.1(0.1)\ 1.7$, $2.0(0.2)$ and 4.0; $f_\lambda = 0$ to 3; $\omega = 0.5(0.5)$ and 4.0
Curtiss Wright - P537-U-26 APL/JHU Rep. CM-469	Keller, E. G., Black, S. D., Czuba, T., and Pengelley, C. D.	Supersonic Airforce Coefficients for Flutter Analysis. April 1948	Same as above + r's and g's L_L, L_α, M_h, M_α - (Leading edge)
NACA TN 2055	Huckel, V., and Durling, B. J.	Tables of Wing-Aileron Coefficients of Oscillating Air Forces for Two-Dimensional Supersonic Flow. March 1950	$M = 10/9$, 10/8, 10/7, 10/6, 2, and 2.5; $x_1 = 0.1(0.1)$ and 0.9; $\omega = 0.02$(irregular) 20
USAF Technical Report No. 6200	Luke, Y. L.	Tables of Coefficients for Compressible Flutter Calculations. August 1950	$M = 10/9$, 5/4, 10/7, 10/6, 2, 2.5, 10/3, and 5; $1/k = 0.5$(irregular) 100 approx. (Axes 1/4 chord) L_h, L_α, M_h, and M_α
Navy Dept. Bur. of Ord.	NAVORD Report 1488 (Vol. 4)	Handbook of Supersonic Aerodynamics. January 1952	Aero. Force Flutter Coefficient C_L and Moment C_M (Arbitrary Axis) $M = 1.1(0.1)\ 2$, $2.0(0.2)\ 4.0$, 4.5, $5(1)\ 12 = 2kM^2/M^2 - 1$
NACA TN 3606	Huckel, Vera	Tabulation of the f_λ Functions Which Occur in Aerodynamic Theory of Oscillating Wings in Supersonic Flow	$M = 1.2$ -5.0, $\lambda = 0$ to 11, $k = 0$(irregular) 2.0
NAVORD Rep. 1234	Miles, John W.	On Harmonic Motion of Wide Delta Wings at Supersonic Speeds	$M = 10/9$, 10/8, 10/7, 10/6, 2, 10/4, 10/3, and 5 $k = 0$(irregular) 4.8 f_0 f_4
Luftfahrtforschung BD 20, Lfg. 12	Schwarz, L.	Undersuchung einiger mit den Zylinder funktionen mullter Ordnung verwandter Funktionen. Fet. 1944, pp. 341-372	
Douglas Aircraft Co. Rep. SM-14771		Supersonic Aerodynamic Lift and Moment Coefficients	$M = 1.2$, 1.4, 5/3, 2.0, and 2.5 Reference axis - 50-percent chord

TABLE II.- AVAILABLE THEORETICAL OSCILLATORY AERODYNAMIC FORCES - Concluded

[Based on two-dimensional linearized subsonic and supersonic flow theory]

Source	Authors	Title	Range of parameters and remarks
NACA TN 2590	Nelson, H. C. and Berman, J. H.	Calculations on the Forces and Moments for an Oscillating Wing-Aileron Combination in Two-Dimensional Potential Flow at Sonic Speed	$x_1 = 0.1(0.1)$ and 0.9 (wing chord); $k = 0.01$(irregular) 3.5
Forschungsbericht Nr. 1071	V. Borbely	Uber die Luftkrafte die auf einen harmonisch schwingenden zwridimensionalen Flügel bei Uberschallgeschwindigkeit wirken	$M = 1$, 10/9, 10/8, 10/7, 10/6, 10/5, 10/4, 10/3, 10/2, and 10; $\omega = 0(0.5)$ 10.0
Convair Rep. No. ZS-115-003	Dublin, M.	Computation of Supersonic Oscillatory Air Force Coefficients - 1948	
Convair Rep. ZU-001		Charts of Supersonic Oscillatory Air Force Coefficients on Movable Surfaces. 1948	
British Rep. Trans. No. 866	Jordan, P., and Gawehn, M.	Unsteady Aerodynamic Coefficients for Supersonic Flow Part II - Numerical Tables	$\frac{1}{M} = 0.1(0.05)$ 0.4(0.1) 0.8(0.05) 0.9 $\log k = -\infty$; -3(0.05) 0; $\tau = 0.05(0.05)$ 0.3
Lee Arnold Assoc., Inc.	Arnold, Lee 1953	Tables for the Computation of Unsteady Supersonic Generalized Aerodynamic Forces on a Delta Wing With Arbitrary Deflection Mode Shapes	$M = 1.75$, 2, and 3 Tables of η_{mnp} q $1/k = 0.9$ to 56.25 (13 values)
Office Nationale d'Etudes et de Recherches Aero.	Weber, R. 1950	Tables of Unsteady Aerodynamic Coefficients in Supersonic Flow. Part II - Numerical Tables of Nonstationary Aerodynamic Coefficients Part III - Graphical	$M = 10/9$, 10/8, 10/7, 10/6, 10/5, 10/4, 10/3; $\omega = 0.05(0.025)$ 2.0; $\tau = 0.05(0.05)$ 0.5, 0.6, and 1.0
NACA TN 3286	Lomax, H., Fuller, F. B., and Sludер, L.	Generalized Indicial Forces on Deforming Rectangular Wings in Supersonic Flight	$M = 1.1$, 1.2 $AR = 4$ values of F^{ln}_{jg} for $n = 0(1)5$, $l = 0,1$ $j = 0$, 1, and 2
Rep. No. 8632 Lockheed Aircraft Corp.	Fuller, F. E., and Siegel, S.	Tables of Two-Dimensional Compressible Flutter Coefficients Referred to the Mid Chord	Data from NACA Rep 846, NACA TN 2590 and USAF Tech. Rep. 6200 converted to k^2A nomenclature and tabulated for interpolated $1/k$ values. Each $1/k$ is in the ratio of the sixteenth root of two times the preceding value

TABLE III.- PARTIAL LISTING OF EXPERIMENTAL FLUTTER CHECKS

Source	Author	Configuration	Aspect ratio	Speed range	Type of air forces used	Type of flutter analysis used	Agreement with experiment
NACA TM 887	Cicala, P.	Cantilever, unswept, uniform wing	3 and 6	0 to 55 fps	Two-dimensional, incompressible	2 degrees of freedom	Good for speed, frequency, and amplitude ratio
ARC R & M No. 1943	Frazer, R. A., and Skan, S. W.	Unswept, tapered (λ = 0.52); bending springs at root	5.8	low	Modified two-dimensional, incompressible	2 uncoupled modes Rayleigh type	"Excellent" agreement of speed and frequency (see R & M 1945)
ARC 6752-[illegible].348, June 9, 1943	Williams, J.	Unswept, tapered	5.8		Measured coefficient	2 modes	Good
NACA Rep. 966	Runyan, H. L., and Watkins, C. E.	Cantilever uniform unswept wing with one concentrated weight moved along span	6	300 to 525 fps	Two-dimensional, incompressible	Differential equation	Very good
AFTR No. 6184	Goland, M., and Dengler, M. A.	Various two-dimensional wing-aileron-tab, experiment of Voigt and Walter	Two-dimensional (end plates)	20 to 100 fps	Two-dimensional, incompressible (4798)	Modal (AFTR 4798)	Very good for pitch-bending or wing. Very good with aileron mass balanced. Poor to good with geared tab or unbalanced aileron.
NACA TN 2375	Woolston, D. S., and Runyan, H. L.	Cantilever uniform unswept wing with one concentrated weight moved along span	6	300 to 525 fps	Two-dimensional, incompressible	2, 3, and 4 uncoupled modes, 2 and 3 coupled modes	Good agreement only with weight at tip and at root. Poor and unconservative agreement with weight part way out on span, not enough modes used.
NLL Rep. F. 122	Bergh, H., and Ijff, J.	Cantilever rectangular wing; mass ratio from 5 to 30		No flutter tests	Measured two-dimensional and theoretical two-dimensional	2 modes	Calculated results with measured air forces sometimes higher, sometimes lower than calculated results with theoretical air forces
NACA Rep. 1014	Barmby, J. G., Cunningham, H. J., and Garrick, I. E.	Cantilever uniform swept and unswept mass ratio 2 to 130	2 to 8	M = 0.2 to 0.85	Two-dimensional, incompressible	2 uncoupled modes swept wing analysis	Good in general (within 20% for most part except for A = 2 unswept)
NACA TN 2558	Woolston and Castile	Cantilever uniform unswept wings; mass ratio 1.4 to 196	4 to 8	M = 0.15 to 0.85	Two-dimensional, incompressible and Reissner correction	3 uncoupled modes	Good to fair for A = 4
NACA RM L51C08	Lauten and Nelson	Cantilever, rectangular, full span-bomb drop	7.3	M = 0.85 to 1.07	Two-dimensional, M = 0 to $\frac{10}{7}$ including M = 1.0	Modal - 2 modes	Conservative - within about 15%
NACA RM L51H09a	Sewall, J. L.	Cantilever, swept (Λ = 34.5°), tapered (λ = 0.43)	4.6	280 to 295 fps	Two-dimensional, incompressible	2, 3, and 4 modes, swept wing analysis V_R	Conservative by 10%
NACA RM L52D24b	Lauten and O'Kelly	Rocket vehicle; (Λ = 45° and Λ = 60°) tapered, λ = 0.54	8.00(Λ = 45°) 4.25(Λ = 60°)	M = 0.89 and 1.09 M = 0.89 and 1.09	Two-dimensional, incompressible	2 modes, swept wing analysis V_R	Conservative by up to 5%

TABLE III.- PARTIAL LISTING OF EXPERIMENTAL FLUTTER CHECKS - Concluded

Source	Author	Configuration	Aspect ratio	Speed range	Type of air forces used	Type of flutter analysis used	Agreement with experiment
NACA RM L55I13a	Unangst, J. R., and Jones, G. W.	Tapered ($\lambda = 0.6$) $\Lambda = 0^\circ$ to 60°	2, 4, and 6	$M = 0.76$ to 1.42	Two-dimensional incompressible	2, 3, and 4 modes swept wing analysis V_R	Excellent to good for high A and high Λ for $M = 1.3$. Fair to poor for low A with low Λ.
NACA RM L51A11	Tuovila	Cantilever uniform $\Lambda = 30^\circ$ to 60°	1.50 to 4.10	$M = 1.3$	Two-dimensional incompressible	2 modes, swept wing analysis	Conservative but poor except for $\Lambda = 60^\circ$, higher A
NACA RM L50C15a	Widmayer, Lauten, and Clevenson	Cantilever, uniform, unswept, except one $\Lambda = 15^\circ$	2 to 13	$M = 0.2$ to 0.92	Two-dimensional incompressible	2 modes	Good to fair, except $A = 2$. A number of unconservative results indicated need for third mode in analysis.
NACA TN 3311	Cunningham, H. J., and Lundstrom, R. R.	Cantilever, uniform, unswept wing on rocket model	7	570 and 630 fps	Two-dimensional incompressible	2 wing elastic modes, 2 body freedom	Conservative by 35%
NACA TN 3301	Nelson, H. C., and Rainey, Ruby	Cantilever, uniform, unswept	3.0 to 4.55	$M = 1.3$	Two-dimensional, $M = 1.3$; rectangular wing, $M = 1.3$	2 modes	Mostly conservative. Rectangular wing section coefficient in strip analysis generally gave best results.
Curtiss-Wright Report H-47-3	Flutter section	Root restrained by springs, uniform, unswept, and $\Lambda = 45^\circ$. Mass ratio from 130 to 400	3.11($\Lambda = 0^\circ$) 1.56($\Lambda = 45^\circ$)	$M = 0.35$ to 0.93	Two-dimensional incompressible and also Biot's aspect-ratio correction	2 modes	Conservative results with two-dimensional air forces. Slightly unconservative after aspect-ratio correction. Aspect-ratio correction brought about a marked improvement in agreement of flutter frequency and amplitude ratio.
AFTR 6353	Andreopoulos, T. C., Chee, C. F., and Targoff, W. P.	Tapered half-span wing held at root for antisymmetric oscillations, with two simulated engines and aileron	10	Up to 300 mph	Incompressible two-dimensional and various aspect ratio corrections	Modal - uncoupled and coupled	Strongly conservative with two-dimensional air forces. Very good agreement with a modified aspect-ratio correction, except for aft engine center-of-gravity location which gave violent unconservative results. No significant difference found from using coupled and uncoupled modes.
Max Plank Inst. report No. 5, 1952	Drescher, H.	Two-dimensional fin and rudder in a water tunnel	(Two dimensional)	Re = 600,000 in water	Two-dimensional	No flutter	Hinge moment and pressure distributions for step function type motions. Qualitative agreement good, quantitative agreement from good to fair.
Princeton Univ. Aero. Eng. Dept. Rep. No. 335	Goland, L. and Perlmutter, A. A.	Two-blade helicopter rotor; 13-foot diameter (XH-17 model of Brooks)		175 to 300 fps	Two-dimensional (strip); C(k) used for the representative stations taken at 75% semispan	2-mode (first bending which was essentially blade flapping, and first torsion which included pitching flexibility at the root)	Conservation for lowest pitch control stiffness, unconservative for all greater pitch control stiffness.
ARC 5668 ARC 5917	Frazer, R. A. and Jones, W. P. Scruton, C, Williams, J., and Miles, C. J. W.	Rigid wing with aileron and tab	4.08 (wing)	0 to 80 fps	"Vortex strip theory" as in ARC 5105 and 5265	2-modes (aileron and tab)	Theoretical conclusions regarding: (1) ratio of aileron density to tab density; (2) addition of mass to aileron; (3) location of tab balance mass were confirmed by experiment on aileron-tab flutter.

TABLE IV.- STATUS OF EXPERIMENTAL FLUTTER MODEL DATA

Configuration		Regime I	Regime II	Regime III	Regime IV
		M = 0.8 at sea level M = 1.2 at altitude	M = 1.2 at sea level M = 2.0 at 30,000 ft and above	M = 3.0 at sea level M = 4 to 5 at higher altitudes to 300,000 ft	M = 6.0 at sea level M ≈ 20 near 100,000 ft and above
		High subsonic-transonic	Transonic-low supersonic	Supersonic	Hypersonic
Clean fixed surfaces (wings, fins, etc.)	Straight surfaces	Generally satisfactory. Fill in data and evaluation required.	Generally satisfactory. Fill in data and evaluation required.	Data needed.	Data needed.
	Swept surfaces	Generally quite satisfactory. Evaluation required.	Generally satisfactory. Fill in data and evaluation required.	Probably will not be used.	Probably will not be used.
	Delta surfaces	Data needed. Understanding required.	Data needed. Understanding required.	Data needed. Understanding required.	Probably will not be used.
	Low aspect ratio combined straight-swept-delta type surfaces (chordwise deformation and higher modes may be important).	Data needed.	Data needed.	Data needed.	Data needed.
*Wings with external stores with and without pylon type suspension	Straight surfaces	Additional data and evaluation required.	Data needed.	Data may be needed.	Probably will not be used.
	Swept surfaces (includes higher-order modes).	Additional data and evaluation required.	Data needed.	Probably will not be used.	Probably will not be used.
	Delta wings	Data needed.	Data needed.	Probably will not be used.	Probably will not be used.
Airfoil section and thickness effects. (From aerodynamic viewpoint in view of piston theory which indicates detrimental effects of thickness).		Exploratory tests needed.	Exploratory tests needed.	Exploratory tests needed.	Exploratory tests needed.
Chordwise flutter		Probably not applicable to this regime	Fill in data and evaluation required. Design criteria need to be established and assessed against aircraft parameters.	Fill in data and evaluation required. Design criteria need to be established and assessed against aircraft parameters.	Fill in data and evaluation required. Design criteria need to be established and assessed against aircraft parameters.

*Basic understanding of store impedance effects needed. Very important problem to find optimum location of stores.

TABLE IV.- STATUS OF EXPERIMENTAL FLUTTER MODEL DATA - Concluded

Configuration		Regime I	Regime II	Regime III	Regime IV
		$M = 0.8$ at sea level $M = 1.2$ at altitude	$M = 1.2$ at sea level $M = 2.0$ at 30,000 ft and above	$M = 3.0$ at sea level $M = 4$ to 5 at higher altitudes to 300,000 ft	$M = 6.0$ at sea level $M \approx 20$ near 100,000 ft and above
		High subsonic-transonic	Transonic-low supersonic	Supersonic	Hypersonic
Flutter prevention devices and optimum configurations from a flutter viewpoint.		Data needed.	Data needed.	Data needed.	Data needed.
Tip controls.		Data needed.	Data needed.	Data needed.	Use unknown. Data needed if used.
**T-tails		More data needed. Evaluation required.	Data needed.	May not be used.	Probably will not be used.
Panel flutter (includes panel flutter of cylindrical missiles or bodies).		Generally satisfactory. Problem needs to be evaluated and design criteria assessed against aircraft parameters.	Generally satisfactory. Problem needs to be evaluated and design criteria assessed against aircraft parameters.	Exploratory tests needed.	Exploratory tests needed for possible configurations.
Floating tip tanks.		Basic data and evaluation needed.	Basic data and evaluation needed.	Probably will not be used.	Probably will not be used.
Control surfaces (includes buzz and mass unbalanced control surfaces)		Flutter-buzz data needed. Damping-stiffness data needed. Basic understanding of buzz needed. Design configurations for avoiding buzz needed.	Flutter-buzz data needed. Damping-stiffness data needed. Basic understanding of buzz needed. Design configurations for avoiding buzz needed.	Control-surface flutter seems not probable for lower modes of clean wings. However higher modes may present problems. Exploratory tests should be made.	Unknown. Exploratory tests should be made
Control surface play limits		Data needed.	Data needed.	Data needed.	Data needed.
***All-movable control surfaces	Straight	Data needed.	Data needed.	Data needed.	Data needed.
	Swept wings	Generally satisfactory. Fill in data and evaluation required.	Generally satisfactory. Fill in data and evaluation required.	May not be used.	May not be used.
	Delta	Needed.	Needed.	May not be used.	May not be used.

**Very important problem.

***Very important problem. Basic understanding and parameter variation data needed.

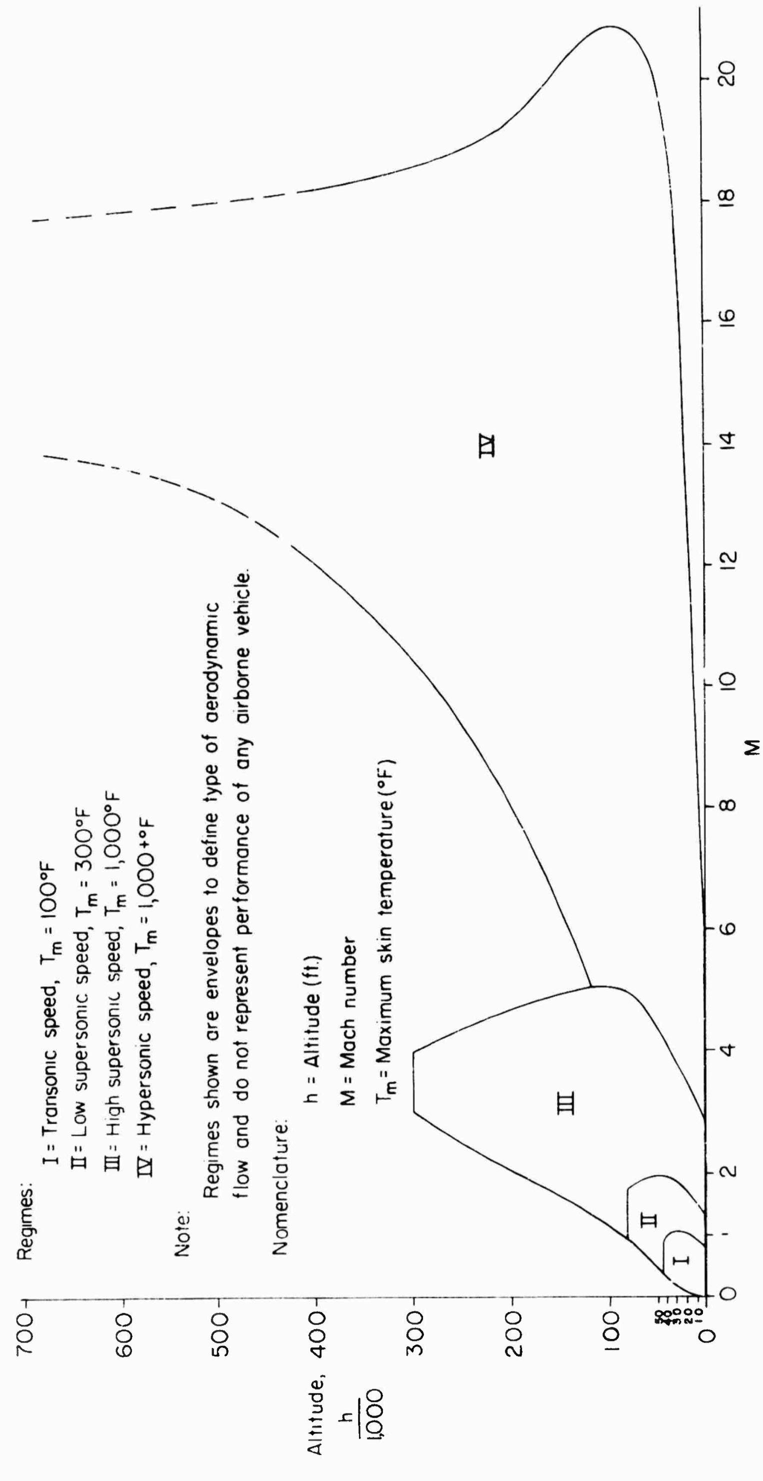
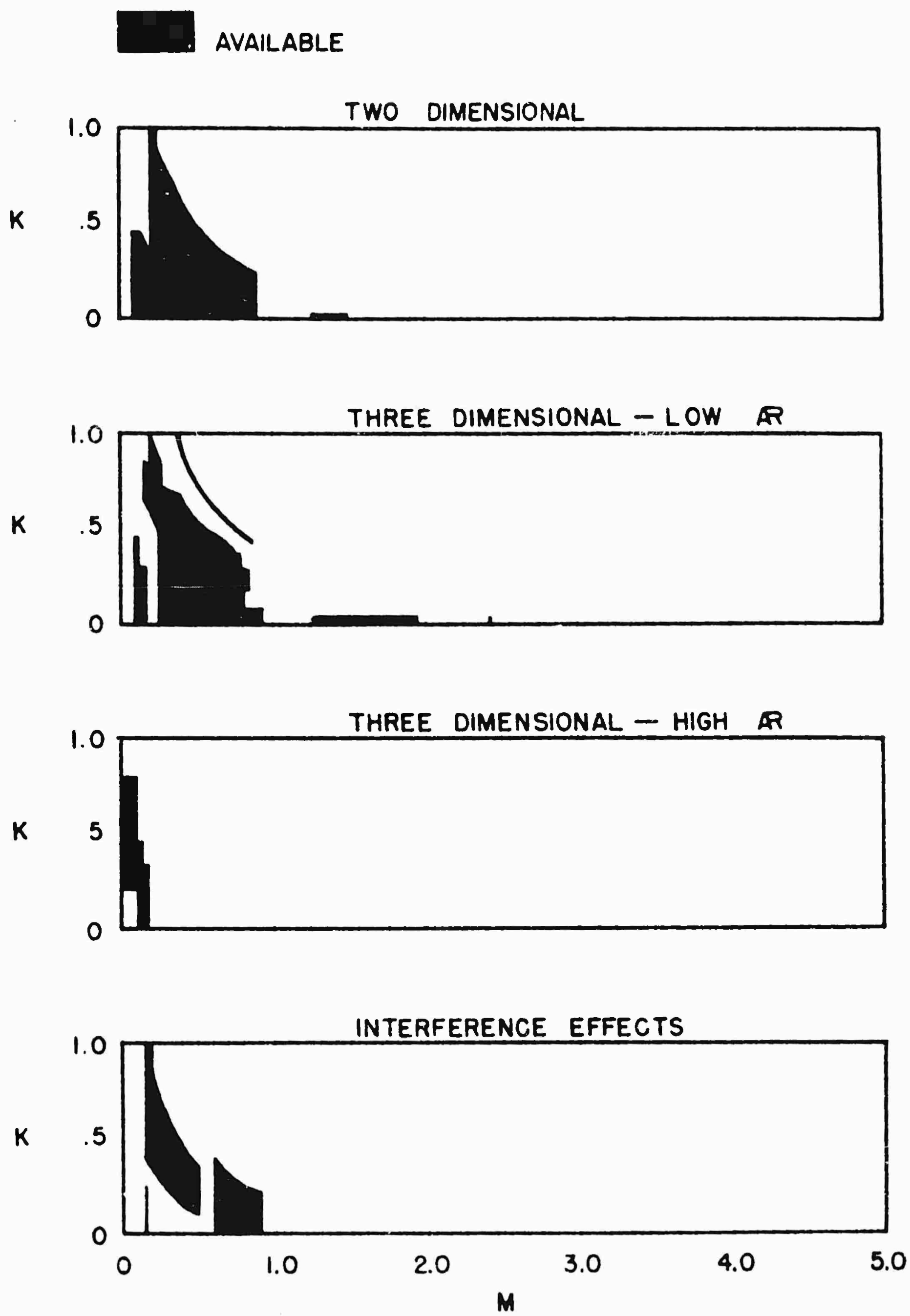
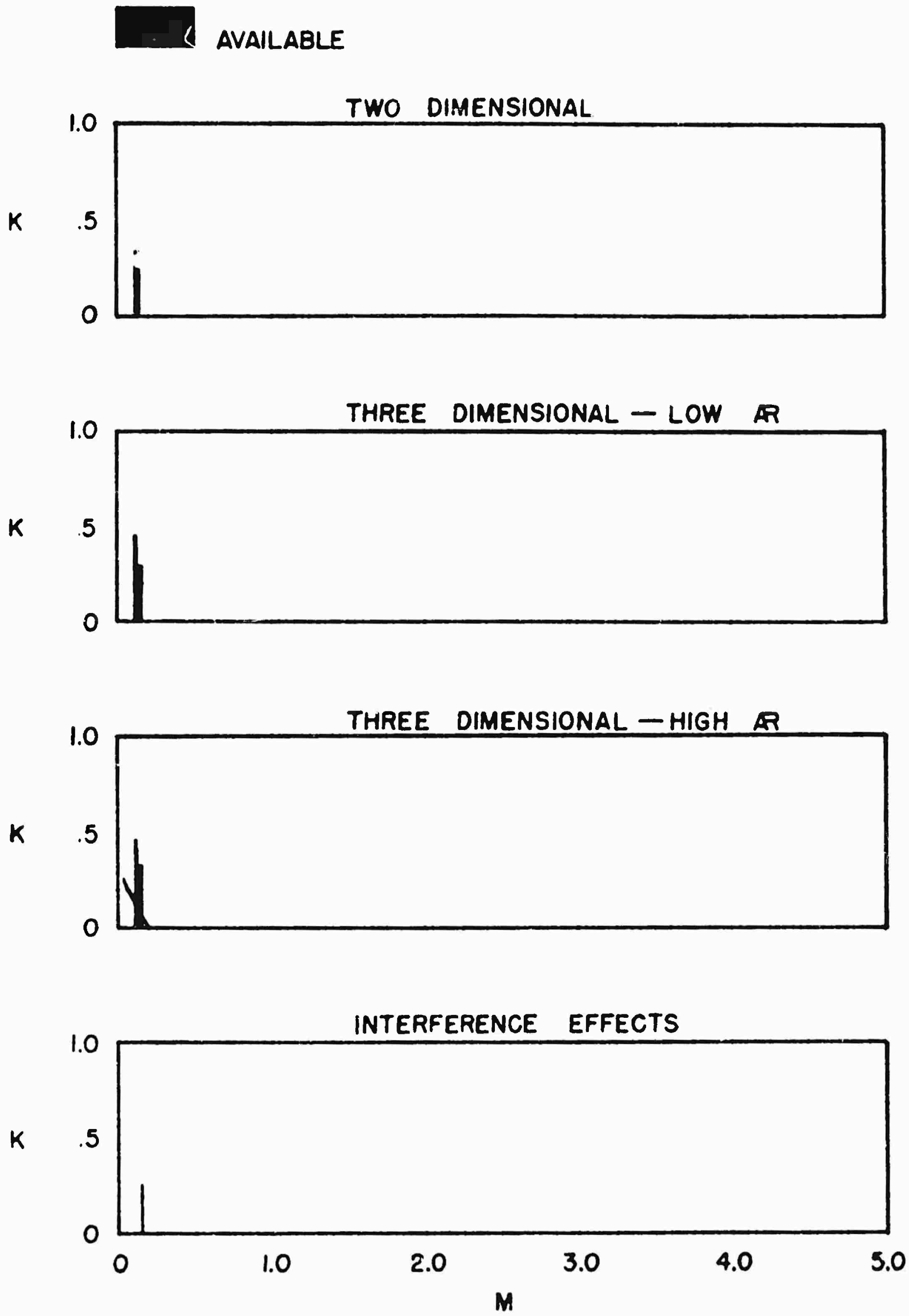


Figure 1.- Airborne vehicle altitude - Mach number regimes.



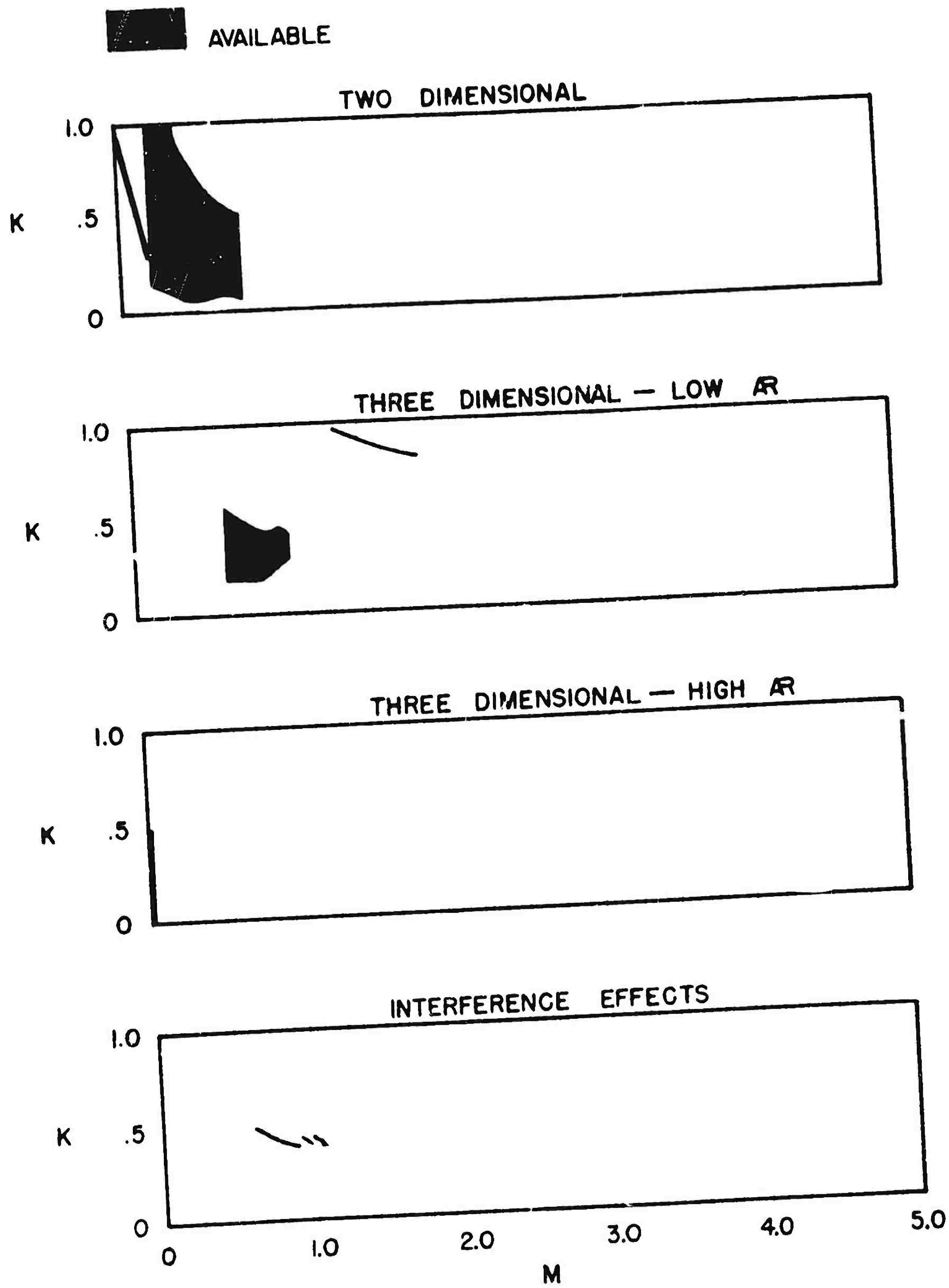
(a) Pitching.

Figure 2.- Availability of experimental oscillatory air forces.



(b) Translation.

Figure 2.- Continued.



(c) Control rotation.

Figure 2.- Concluded.

NACA - Langley Field, Va.